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Research article

Forestry based products as climate change solution: Integrating life cycle assessment with techno-economic analysis

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ABSTRACT

This study establishes an integrated life cycle analysis and techno-economic assessment to evaluate costs and carbon footprint impacts of an integrated forest biorefinery that produces lumber, industrial sugar and wood pellets in a planned biomass conversion center in the Pontiac region of Quebec (Canada). An integrated evaluation approach combining levelized cost and carbon footprint accounting was adopted for assessing the implementation of this novel advanced biorefinery concept taking into account different biomass feedstock, diversified product portfolio (sugar, lignin, bio-oil, electricity and lumber) and multiple biomass conversion technologies. The conclusion of this study is that if the GHG emission is considered as the basis of the ranking system, the production of wood pellets would emit less (1.2 kg/T) and that of lumber, and sugar would emit most respectively (3.3 kg/T and 98.4 kg/DT). This is whereas if the ranking would be performed based on the cost, the sequence would be the production of lumber, pellet, and sugar.

1. Introduction

Due to growing global competition from mills in emerging economies, pulp and paper mills in North America and Europe are increasingly shutting down production lines. Consequently, many rural and remote regions are experiencing revenue shortfalls and job losses in the forestry sector. The pulp and paper industry (PPI) is therefore looking for new value-added products and for more efficient ways to use forest resources. The PPI has the greatest potential to lead the development of bioeconomy. There are several opportunities for the industry to produce new high-value carbon-neutral products from forest biomass resources. Numerous countries are developing forest based bioeconomy plans while considering local specificities (Lovrić et al., 2020). The forest bioeconomy framework for Canada reflects how the constant changes in market conditions have accelerated bio-innovation and underscored the importance of transitioning towards a greener economy (Natural Resources Canada, 2017). Demand for advanced and innovative forest bioproducts, and green employment and partnerships are the main drivers for forest industry sustainability (Natural Resources Canada, 2017).

i) State of the art

In transition from fossil-based fuel and chemicals, bioenergy requires optimizations within both upstream (supply chain) and downstream (biorefinery and sawmill) stages of the wood based value chain products. Optimization and allocations are challenging when multiple products are considered. Assessment of bio-products advantages over fossil-derived ones and related carbon impacts needs integrated decision making framework that consider technical, economic, environmental and social aspects. The lack of integrated frameworks including validated field data inputs for specific regions is a significant challenge.

Moreover, many High Value Products (HVP) and markets for the wood fiber have been sought and identified, such as sugar and wood pellets as feedstocks for the production biofuels, biochemicals and biomaterials. Development of these alternative products needs wood conversion technologies with enhanced yield biomass-to-products, as well

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Abbreviations

BCC	Biomass Conversion Center
BAT	Best Available Technologies
CAPEX	Capital expenditure
CC	Crystalline cellulose
CF	Carbon Footprint
CLT	Cross-laminated timber
FCI	Fixed Capital Investment
FMU	forest management units
HVP	High Value Product
ISBL	Inside the Battery Limits
LCA	Life Cycle Assessment
OPEX	Operational Expenditure
PPI	Pulp and Paper Industry
TEA	Techno-Economic Assessment
TLCC	Total Life Cycle Cost
TCI	Total Capital Investment
TDC	Total Direct Costs
TDEC	Total Delivered Equipment Cost
WFY	Wood Fiber Yard

as reduced carbon footprint and unit operating cost. This need presents several challenges. There is still a knowledge gap in matching the quality and type of feedstock supplied with conversion technologies. Assessing the best available technologies (BAT) for converting wood fibre calls for development of adaptive and complex decision making platforms based on best sustainable business cases. Given the regional variability and the impact of the specific bioenergy and HVP attributes, an integrated analytical framework is required to properly assess process technologies, potential scenarios and pathways.

Considering the above needs, Techno-economic analysis (TEA) and life-cycle analysis (LCA) are the right methods to support such a decision making. TEA evaluates the technical feasibility and economic performance, while LCA evaluates environmental impacts. For sustainable technology development, a trade-off between TEA and LCA should be achieved (Norris, 2001). In the past few years, several LCA and TEA models have been developed separately in case of a single bio-product without accounting for impact of different allocation approaches (Cherubini and Strømman, 2011) (Muench and Guenther, 2013) (Shadbahr et al., 2021). Although, the integration of TEA and LCA is attracted many attentions in recent researches (Dutta et al., 2016), current LCA/TEA based decision making tools often do not include the impact of wood fiber supply chains.

ii) Motivation and objective

Extraction and commercialisation of HVP from wood processing are facing three main challenges. First, relatively higher cost directly linked to wood biomass supply chain calls for the entire value chain optimization. Controlling logistic costs is thus a key factor for deploying HVP pathways. This includes identifying optimal biorefinery location sites and their scale of supply. The second challenge is related to the recalcitrant nature of woody biomass toward deconstruction when compared to conventional pre-treatment technologies. Available primary data at pilot and demonstration scales are insufficient to provide meaningful economic and environmental impacts assessments (Zhu et al., 2010). The third challenge is related to the sustainability of forestry biomass management. For example, in calculation of carbon footprint of the HVPs, allocations across all biomass streams of the entire woody biomass value chain shall be considered. It is necessary to consider the impact of upstream supply chain on all potential products resulting from wood fibers. For example, the different residues and waste streams could be used to produce multiple energy products. Depending on the type of trees, age and health, a wood volume-based allocation could be thus used. Furthermore, sensitivity analysis related to the impact of upstream parameters on midstream and downstream processes and final products are yet to be thoroughly investigated. Whereas the upstream boundary is relatively clear and consistent in the literature, the midstream consisting of the biomass conversion center (BCC) is often under investigation. A BCC consists of the wood fiber yard (WFY) with different wood fiber conversion units (Fig. 1). The three products (lumber, sugar and pellets) will be affected by both upstream and midstream process units. The allocation approach for the midstream processes is critical in assessing the economic and environmental impact of each product.

The objective of the current work is to develop and validate an integrated decision support framework for an integrated assessment of a wood Biomass Conversion Center (BCC) that includes supply chain logistics. A specific geographical site is considered to assess different wood fiber components, conversion units and products (Shadbahr et al., 2021). Lumber, sugar and pellet have been identified as viable products to provide a sustainable solution for the forestry sector to replace and/or complement current pulp & paper pathways. Proposed BCC including three biomass processing units is currently under consideration for implementation in Pontiac (Quebec, Canada). An accounting framework for the embodied carbon of each product will be developed. This will prevent double counting of biogenic emissions due to land-use change and product use. For this, allocation of common processes between the different downstream products will be developed. Different allocation methodologies will be used to estimate cost and carbon footprint of each product.

iii) Innovative contribution

Converting woody biomass to sugar requires the development of advanced fractionation technologies enabling enzyme access to the cellulose and hemicellulose fractions during the saccharification step (Karinkanta et al., 2018). Recalcitrance of wood based lignocellulosic to delignification limits the recovery of the different components. Research has emerged in investigating beyond the conventional pulping process. A steam pre-treatment to first extract the hemicellulose fraction followed by a delignification step to produce cellulose fraction has led to high recovery rate of potential HVP (Tian et al., 2017). Thermochemical pre-processing is scalable and effective at separating the different wood components but require significant chemicals as input (Gao et al., 2013). This leads to additional post treatment steps to remove unreacted chemicals and other by-products including inhibitors. Furthermore, thermochemical pre-processing techniques are difficult to downscale to meet the needs of decentralized wood based sugar production (Chundawat et al., 2011) (Brandt et al., 2018). Mechanical pre-treatment enables a modular system design for pre-processing even if initial energy input is relatively higher when compared to thermochemical pre-treatments.

The impact of upstream logistics should be computed to account for potential local sensitivity and regulations. The midstream steps consist of three different conversion units that could be part of a biomass conversion center (BCC).

- Conversion unit #1. It consists of sawmill unit converting log to lumber products.
- Conversion unit #2. It consists of a sugar biorefinery converting the remaining part of a log to sugar. Wood chips from sawmill residues will be also used as feedstock in this unit.
- Conversion unit #3. It consists of palletisation unit using forest residues and lignin by-product from the sugar biorefinery unit as the main feedstocks.

Densification of the different wood residues is the best option to reduce downstream transportation and delivery logistics. These residues

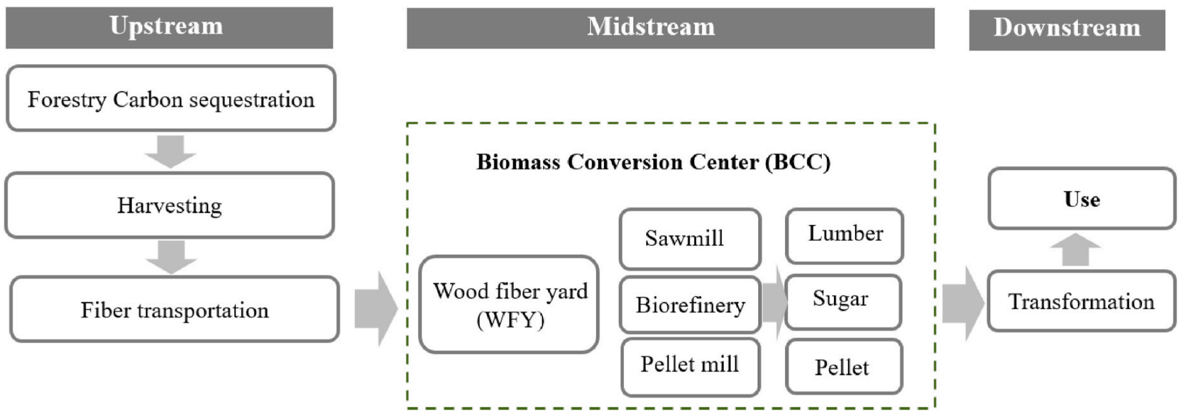


Fig. 1. Cradle-to-Gate stages contributing to cost and GHG inventories of wood based products.

will be chipped and then dried. Different fuel pellet options have been considered and range from small scale CHP units for remote communities to large scale power plants. Mobile pyrolysis could address logistic, cost and carbon footprints challenges. However, for now these options are not yet developed enough and are not considered in this study.

Lumber remains the key driver of the forestry industry and will be considered as the primary product in this study. We therefore focused on assessing the impact of its production in this work, although new higher value applications are being considered for harvested logs (Ramage et al., 2017). However, other traditional forest products (plywood, oriented strand board, particleboard, glue timbers, laminated veneer lumber, etc.) and emerging bulk wood building products such as cross-laminated timber (CLT) and glulam are not considered in this study. In this sense, the main novelties of this study can be summarized as 1) developing a new LCA/TEA integration model for forestry-based products; 2) Evaluate three forestry HVP to find the most environmental/economic friendly product; 3) Implementing the proposed approach in a real case study of the Pontiac BCC in Quebec, Canada.

The remaining of the paper is organized as follows: In section 2, conversion units with more details are explained and the methodology for both technical and economic analysis are described. In section 3, the result for LCA and TEA of Pontiac BCC is provided to validate the methodology presented. Section 4 includes a discussion regarding the result obtained from the case study. Finally, in section 5, conclusion is provided.

2. Methodology and conversion units

In this section, a bottom-up approach to estimate financial and carbon footprint impacts of lumber, sugar and pellets is discussed. Cost and GHG emissions contribution from upstream logistic are estimated based on published methodology from our previous work (Shadbahr et al., 2021). Contribution of biogenic carbon will be also estimated. This methodology will provide an allocation of the upstream stage between the different products. Impact of different scenarios will be assessed. In some cases, a technology benchmarking will be also undertaken.

2.1. Product life cycle assessment and system boundary

It is often assumed that wood-based products are carbon neutral since any carbon that is released through the process of burning or use of wood for energy is recaptured through the sequestration of the wood (Johnson, 2009). Similarly from the financial point of view, biomass is often considered as free. These two assumptions are often not correct. CO_2 removal from the atmosphere during the biomass growth stage should be balanced by GHG emissions during logging, transport, processing and end-of-life stages (Janowiak and Swanston, 2017). With high logistic cost structure and lower density, wood feedstock is more expensive than crude oil. Variability in composition and structure of wood fiber gives rise to additional challenges even when compared to other feedstock like sugar cane. Variable composition and longer growth are two examples. However, as a raw input material, wood provides potentially higher socio-economic advantages.

To quantify total life cycle cost and carbon footprint of each product, the upstream process steps and their allocations are assessed. Common to the three main wood-based products considered in this study, cost and carbon footprint incurred during the upstream stages will be allocated under different scenarios. Following the wood harvesting and processing, the fiber volume used for each processing unit could vary depending on the type of tree and available quantity of residues. The different scenarios will be described below.

System boundary impacts and the carbon/cost budget methodologies are critical in assessing the viability of different product pathways (Bui, 2018). Fig. 2 indicates the overall system boundary for this study. As shown in the Figure, in the upstream supply chain starts with harvesting and collection. This is followed by roadside storage of harvested logs and residues. Next stage deals with transportation of logs to the WFY within the BCC. In the WFY, logs are debarked and head-sawn and then based on the size, sawnwood are moved to sawmill or biorefinery for lumber and sugar production. Sawmill and biorefinery generate residues used as feedstock in the wood pellet production. In the pellet mill, residues are dried and pelletized.

Logs are transported to the WFY where debarking is carried out. Next, three conversion units are used to produce lumber, sugar and pellet. There is a significant integration between the different units. Residue from one unit is an input for another. Lignin by-product from the sugar production unit is used for the pellet production. This addresses the challenge of finding a market for the lignin. Residues from the different stages of the sawmill unit will be used for the sugar production. Currently, sawmill chips represent around 25% of wood used in pulp industry (Kallio, 2001), (Olofsson and Lundmark, 2016). Assigned biomass ratio of each unit and the corresponding cost and embodied carbon attribution will be critical. This approach and the overall system assessment represents the main novelty of the proposed framework.

The required heat and electricity for different operation units are fulfilled differently. Electricity needs are fulfilled using Quebec (Canada) grid electricity (Khadem et al., 2022). For the heat, a boiler is used to satisfy internal needs. For this purpose, residues from primary sawmilling stage are used as feedstock. Detailed description of the process in WFY and the conversion units are provided in the following sections.

2.1.1. Wood fiber supply chain and wood fiber yard

Geographical site, wood source and the upstream stages have been described in recent publication (Shadbahr et al., 2021). Located in South Western part of the province of Quebec, the proposed integrated

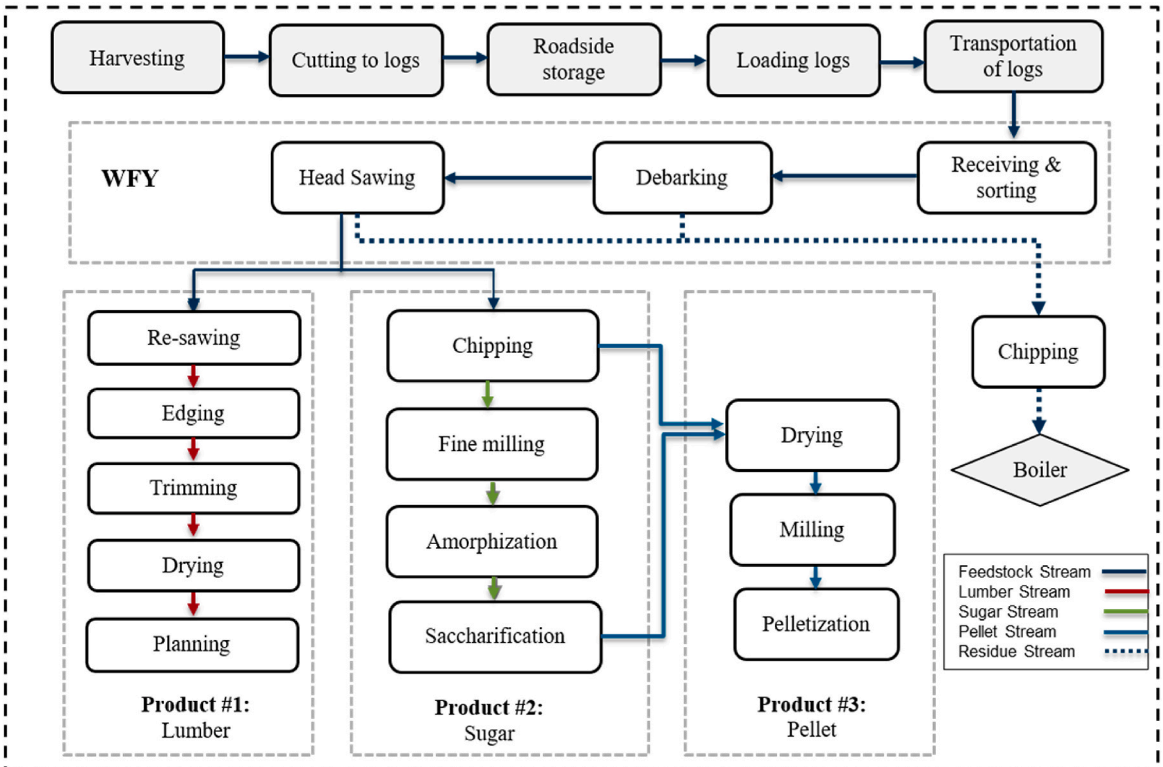


Fig. 2. Schematic representation of key downstream process for the bio-products.

biorefinery include the wood processing yard and the three conversion units. Harvested wood supply logistic has been covered by the authors in details in a recent publication (Shadbahr et al., 2021) and it is not covered in details in this study. Cost and GHG impact per unit volume has been estimated for three products. Once logs are delivered to the BCC site, they are scaled and inspected for defects, and identifying the tree species for the purpose of tracking the volume. A debarker is used to remove bark from the log. In the debarking drum, logs moves along the rotating drum and the bark is removed by scrubbing when logs rub and hit each other. This step occurs at the wood fiber yard (WFY). Debarked logs are directed to the sawmill facility using specialized handling equipment to be cut into lumber.

2.1.2. Lumber production

Sawmills are used to produce softwood lumber but occasionally hardwood is also used. Several differences exist between softwood and hardwood lumber. Lumber from softwood is mostly used in construction. Other applications involving the use of hardwood and lumber include furniture and selected construction. For simplicity, the softwood and hardwood are not distinguished as feedstock for the different production units. The typical operations involved in the sawmill case study are depicted in Fig. 3 and include.

- Logs sorting according to end-use, species and/or size followed by a debarking step and placed on log turner.
- Log edge sawing: Small pieces are cut at both edges of the debarked log.
- Cuts: preliminary cuts are made using a head-saw. Unfinished planks (flitches) and unfinished log (cants) are obtained. Cants are further reduced to multiple flitches.
- Wood slabs with different dimensions are cut using a saw from a log held on a carriage.
- Trimming and finishing. The flitch ends are trimmed to standard lumber lengths.
- Sorting the lumber into different size and grouping the different sizes.
- Drying of lumber and wood chips residues.
- Packaging and shipping.

A recent study provided a completed CF of lumber passed product (Lan et al., 2020). Using CLT as the end product, they established the impact of CO2 emission time using a dynamic LCA.

2.1.3. Sugar production

The biorefinery consists of two integrated conversion units: Sugar syrup and pellet. The wood fiber to sugar conversion unit requires two

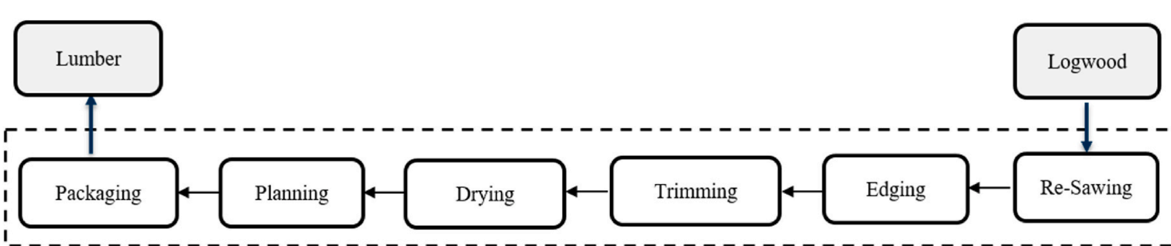


Fig. 3. Key steps of sawmilling process.

main steps. First, a mechanical pre-treatment is performed to enable obtain micronized wood particles. This step is followed by a saccharification step. As shown below, two additional milling steps are required using fine milling and amorphization. Process flow chart for mechanical pre-treatment of biomass using a three-stage milling process is summarized in Fig. 4.

During the saccharification stage, the micronized wood is hydrolyzed by cellulolytic enzymes yielding a slurry containing of different C5/C6 sugars (Borand et al., 2020). A filter press is used to remove hydrolyzed residuals from the sugar products. Additional steps are required to recover more sugar from the residuals. Following an evaporation step, sugar syrup (49% solids) is obtained (Brandt et al., 2018). The residual lignin product is used in the pellet production unit.

2.1.4. Pellet production

The pellet production unit will combine fine milled wood with residual products from the previous saccharification step Fig. 5. The saccharification residues consists mostly of lignin which will be used as a pellet binder (Brandt et al., 2018). Small amount of undigested cellulose and hemicellulose are found in the saccharification residual. Given the high water content, a drying step of the biorefinery residues is required before mixing with the feedstock input for the pellet unit. Other residues requires also a drying (Brandt et al., 2018). After cooling, pellets are screened according to size, and the fines are returned back for pelletization requiring on average 0.15 kWh of electricity per oven dry kg.

Descriptions of the methodology used to quantify cost and carbon footprint of each product are provided below in section 2.3. In both cases, a life cycle assessment approach with similar key process units is used.

2.2. Financial impact assessment

Financial impact assessment will be conducted separately for the sawmill unit and the combined sugar and pellet units. Lignin by-product will be used in the production of wood pellets. Cost assessment of pellet and sugar will be done using process flow reported by Brandt et al., 2018) (Brandt et al., 2018). Cost analysis approach developed by the authors for forestry bioenergy systems (Ahmadi et al., 2020) is adapted to the current study. In this approach, the capital and operating cost reflects the process (technical) and cost (economic) parameters of each conversion unit. Once all the capital (CAPEX) and operating (OPEX) costs have been obtained for each conversion unit, they were assigned to the main products.

In a recent publication, a three scale options for the total amount of wood fiber delivered to the BCC site is considered (Shadbahr et al., 2021). For these three scales, the amount of delivered wood fiber is 50, 000 m^3 (small scale), 250,000 m^3 (medium scale), and 700,000 m^3 (large scale). As a base case, a medium scale was assumed which means that total delivered wood fiber is set at 250,000 m^3 per year.

A techno-economic analysis was conducted for three productions including, lumber, sugar, and pellet. Capital and operational costs varied between these productions, but financial assumptions were almost the same (Table 1). 2021 is the base year used throughout this study, the plants were funded with 30% equity, a loan interest rate of 8%, and a ten-year term. A financial analysis was used following the method outlined by Brandt et al. (2018) (Brandt et al., 2018) (see Table 2).

2.2.1. Capital costs (CAPEX)

The capital cost for each process can be discussed in different terms. In this study, capital cost is considered equal to the total capital investment (TCI) which is including following cost elements: Equipment, installation, buildings, site preparation, and working capital. To determine the fixed capital investment (FCI), ratio factors, which is a very common approach for estimating capital cost (Martinkus and Wolcott, 2017) is applied. This methodology estimates total direct costs (TDC) and FCI from the total delivered equipment cost (TDEC) of major equipment located inside the battery limits (ISBL). The capital cost elements for sugar and pellet process are scaled from Brandt et al. (2018) (Brandt et al., 2018).

2.2.2. Operating cost (OPEX)

The operating cost mainly consists of maintenance, electricity, feedstock, and labor cost. The cost of labor and electricity are adopted from Brandt et al., 2018). The cost for delivered feedstock assumes a facility scale of 184 k bone dry metric ton (BDMT)/yr. The operating costs are dominated by electricity. The OPEX for pellet manufacture includes electricity and natural gas costs for this department, which are not included in the overall electricity and natural gas costs.

2.3. Carbon footprint (CF) accounting

CF accounting is critical and should include all the life cycle stages with product use and end-of-life. This is often referred as the cradle-to-grave LCA. In some cases, a cradle-to-gate approach is privileged when focussing on the impact of upstream supply chain and mid-stream production. The lack of end-of-life data prevent performing cradle-to-grave assessment. The main goal of this study is to compare the end products, which assumes the use stage does not lead to significant variation between fossil and biosourced products. For this reason, in this study, we will mostly focus on a Cradle-to-Gate approach to quantify CF.

A CF accounting framework for forestry products should include the following stages (Mancini et al., 2016).

- Forestry harvesting. This includes fuel used to power equipment for harvesting, load and transportation to Wood yard.
- Sorting and distribution to different conversion units
- Conversion units
- End-of life

This framework should also include a transparent accounting approach to biogenic carbon. This biogenic carbon refers to CO_2 converted by plant through photosynthesis. It is estimated that 30% of produced biomass (stem, branches, and leaves) is above ground and the rest is in the soil (Anderson, 2021). Different accounting rules are applied for biogenic carbon depending on the type of wood and how it is managed. In the context of the current case study and sustainable forest management, only the log removed from the forest is considered as a negative carbon. More detailed and dynamic carbon accounting models

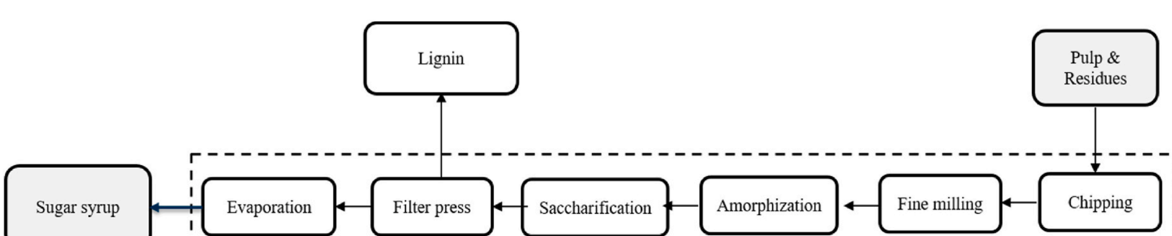


Fig. 4. Key steps of sugar production process.

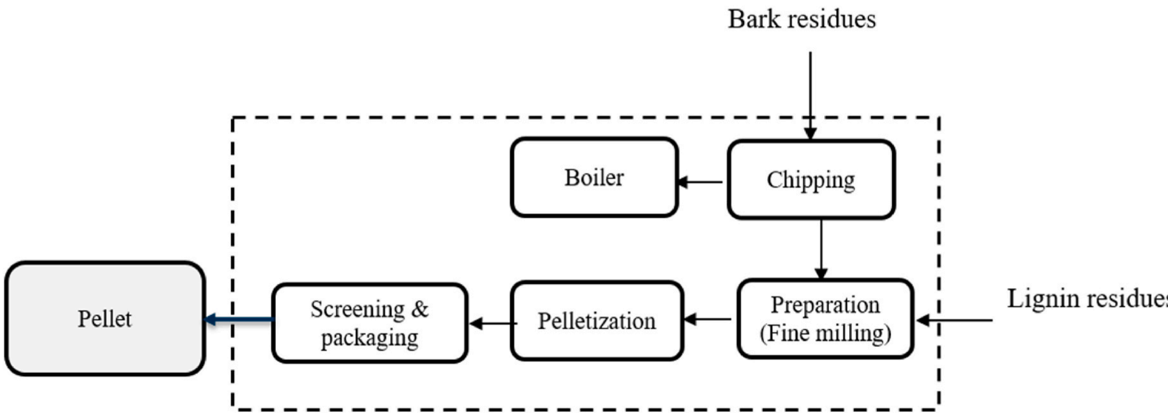


Fig. 5. Key steps of pellet production process.

Table 1
Input parameters for economic analysis of three products.

Economic Parameter	Value
Cost Year	2020
Plant financing	30% equity
Plant Life	20 years + 3 years for construction
Income tax rate	16.9%
Inflation	2%
Land	1.5% TCI
Working Capital	20% OPEX
Ratio Factor (FCI)	4.4
k BDMT/yr through process	184
days per year	329
hours per day	24
Feedstock Cost ($/BDMT)	$56.85
electricity cost ($/kwh)	$0.042
natural gas cost ($/k cf)	$8.8
natural gas cost ($/MMbtu)	$8.6
Sugar Yield (BDMT/BDMT)	0.33
Sugar Produced (BDMT/yr)	60,249
Wood Pellet Yield (BDMT/BDMT)	0.68
Micronized Wood Yield (BDMT/BDMT)	0.91

Table 2
Key techno-economic input parameters for the base case.

Biomass component	Description	Product	Net biomass allocated to each production unit CFi (M3/yr)
W_b	Bark with some wood fiber shaving	Pellet	10% 25,000
W_l	Roundwood used for lumber production	Lumber	30% 75,000
W_m	Sawmilling residues	Pellet	20% 47,500
$W_{m\text{-}h}$	Portion of sawmilling used for lumber drying	Pellet	2500
W_{ps}	Pulp wood for use in the biorefinery	Sugar (cellulose)	16% 40,000
W_{pl}	Pulp wood for use in the biorefinery	Lignin and lignocellulose residues (Pellet)	24% 60,000

should be considered if product certification is required (Morris et al., 2021).

2.3.1. Imbedded carbon – biogenic carbon

The methodology to estimate the net CO_2 following harvesting and transformation of forest biomass is described below. It does not consider emission timing and end-of life. Under a sustainable forest management, sequestered CO_2 during forest plantation lifetime should surpass the emission following harvesting. Thus, an attributional LCA framework based on current year could be used to quantify carbon footprint. This helps assess the carbon footprint related to specific activities instead of assessing global regional or national inventories. As an example, total CO_2 sequestered in dried timber with a density of 400 kg/m3 and 12% of dry mass as moisture is estimated from the dry mass of 357 kg/m3 (Anderson, 2021). Thus, the carbon is estimated as half of the dry wood equivalent to CO_2 sequestered in 1 m^3 of timber, which is 178.5 *44/12 = 655 kg CO_2/m^3.

Life time carbon sequestered in a log wood (C_{LW}) by a tree, often referred as the biogenic carbon, could end up in multiple products. The following sub-categories of wood biomass feedstock (m^3) and products are considered (Table 2).

- Fiber yard residue (mostly bark with some wood fiber shaving) used as feedstock for pellet (W_b)
- Mill residues used as feedstock for sugar production (W_m)
- Roundwood used for lumber production (W_l)
- Pulp wood used for sugar production (W_p)

The corresponding carbon footprint (tonnes of CO_2 per m^3) of each input/output material is represented by CF_i (i = b, m, l). Other potential contributors to net carbon accounting, not considered here, include.

- Carbon soil (Cs)
- Forest residue (small roundwood) used to produce wood chip for pellet (Wr)
- Non-merchantable forest biomass (slash) which is left onsite (Wn)

The harvesting stage will lead to a redistribution of carbon between different carbon pools. More specifically, the biogenic carbon accumulated in trees and soils will be redistributed in the following pools.

- Soil: change in mineral and organic soil carbon contents
- Atmosphere: emission from residue decomposition, and feedstock transport.
- Products outputs: lumber, pellet and sugar

It is assumed that both organic and inorganic component of Cs will not change (Eggleston et al., 2006), (Bergman et al., 2014a). In reality, soil drainage following harvesting have an impact on soil carbon composition. This is canceled by carbon source from wood residues left onsite. For a given total volume V [m^3] of harvested wood, the following equation is used to estimate sequestered CO_2 (CFi) in each component

(Wi) of the logged wood:

$$CF_i \text{ (tonne } CO_2\text{-eq)} = V \times Wi \times [0.6 \text{ t-C/m}^3] \times [3.67 \text{ t-}CO_2\text{/t-C}] \quad (1)$$

Where 0.6 t-C/m^3 is the conversion factor for a wood volume to a tonne of carbon, and the factor 0.5 correspond to the fact that half of dried delivered log wood consists of carbon (Anderson, 2021). The factor "3.67" is related to the ratio of CO_2 molar mass (44) to carbon atomic mass (12), corresponding to a conversion factor from tonnes of carbon to one tonne of CO_2eq.

As mentioned in the above, four main fibre components of log wood are considered in this study. This includes fiber yard residue (Wb), mill residues (Wm), roundwood/logs (Wl) and pulp logs (Wp). Equation (2) provides a breakdown for the biogenic carbon (BC) into seven terms corresponding to different carbon components of the whole biomass tree and soil:

$$CF_{LW} = CF_b + CF_m + CF_l + CF_p \quad (2)$$

The relative amount and composition of each of these four components may vary depending on the tree species and age. Roundwood consists on average of 45% cellulose, 25% hemicelluloses, and 25% lignin (Novaes et al., 2010). Thus, the Wp component of the roundwood consists of two sub-components.

- W_{ps}: sugar product
- W_{pl}: all the residues consisting of lignin and lignocellulose used for pellet production

Based on this and a 50% water content, the total nominal amount of wood (and product) for the three products is.

- Lumber: 75,000 m^3 of wood or 37,500 tonnes of lumber
- Sugar: 40,000 m^3 of wood or 20,000 dry tonnes of sugar
- Pellet: 135,000 m^3 of wood or 67,500 tonnes of pellet

3. Results

Cost and GHG emissions results for each product are discussed separately as follows. There are significant uncertainties when estimating wood fibre fraction used in each product due to location, tree species and maturity, demand flexibility and seasonal variability. An average carbon content of 43% and 35% have been considered for round wood and pulp chips respectively. The remaining portion of biomass is either used for other lower value applications or treated as waste. Sawdust (12%) is partly used as a renewable source of energy within the sawmill unit. Bark and other waste (10%) are often not used although new processes are being proposed for their valorization.

To estimate the volume of each wood fibre component, we have to assume the initial amount of harvested wood fibre. The capacity of the sugar unit from pulp fiber is originally set to a nominal size of 65,000 green metric tons (GMT) annually. This is equivalent of 50,000 m^3 using a conversion rate 1.2 GMT/m^3. The total amount of roundwood processed at the BCC is around 3 times this nominal sugar plant. The total roundwood entering the WFY will depend on the relative proportion of wood fiber used in different conversion units. Thus on average, the WFY will receive 250,000 m^3 of roundwood. We will use this value as the nominal quantity of harvested wood fiber. Quebec Province has 59 forest management units (FMU) with an average area of 606,200 (ha). FMU size varies from 13,400 (ha) and 2,987,300 (ha).

3.1. Upstream processes and carbon budget allocation

In this step, carbon sequestration and emissions related to growth and harvesting stages were quantified. The net CO_2 sequestered by a tree during lifetime is represented by C_{LT}. Only a percentage of this sequestered biogenic carbon is converted to products. Tree branches will be used as feedstock for fast pyrolysis unit, assuming this won't affect soil quality (Amutio et al., 2015). Roundwood log is transported to the BCC for further processing. Carbon footprint of each fiber components will be estimated based on the relative volume.

This average may change between softwood and hardwood. With large crown (~30%), hardwood may have relatively less bark and round wood than softwood. Allocated biogenic carbon has been assessed for each wood fiber components (Table 3) using Equation (2).

3.2. Sawmill unit

The results of the techno-economic analysis of the sawmill case study aimed at producing lumber along with chips, bark, sawdust and shavings are presented in Table 4. More importantly, when sawmill is integrated to the pyrolysis, savings on the OPEX can be expected due the share of utilities system installed within sawmill. Furthermore, the sawmill co-products can be used as feedstock in pyrolysis system, which will contribute to reduce the operating cost associated to the feedstock supply that represents typically 30–40% of the total operating cost. According to the result, 1 Tone (T) of lumber costs $18.3 and it requires 139 kWh electricity.

3.3. Sugar

The results of the techno-economic analysis of the sugar production case study is presented in Table 5. The obtained results indicate that the production of 1 DT sugar costs $286.5, and requires 2 L of diesel and 4100 kWh of electricity. This releases 98 kg co_{2eq} to the environment.

3.4. Pellet

The results of the techno-economic analysis of the pellet production case study is presented in Table 6. The pellet production costs $30/tonne and 1.1 kg CO_{2eq} is released.

Table 7 summarizes the cost and GHG emission breakdown of the triple products.

4. Discussions

The total cost and GHG emission of three forestry products which includes both upstream and downstream of the logistics chain was presented in Table 8. Since the upstream process is the same for all products, the cost and GHG emission per unit is equal. According to results obtained, the lumber production costs $108/tonne, which is the cheapest among the other two products, followed by pellet with $120/tonne. In terms of GHG emission, pellet has the lowest level (1.2 kg/T) which is approximately one third of lumber CO_{2eq} emission. In the process of sugar production, the highest CO_{2eq} is emitted.

To provide a benchmark, the baselines for cost and GHG emission is provided in Table 9. Market actual costs for each product is considered as the baseline of the cost, and CO_{2eq} emission obtained in the other studies in the literature is considered as the baseline of GHG emission.

Table 3
Biogenic carbon associated with each wood fiber component.

Wood Fiber Stream	Components	S1
Slash	Wn	−2,199,600
Forest residue	Wr	2,199,600
Fiber Yard residues	Wb	2,199,600
Lumber Portion of sawlog (Wl) volume in the final lumber product (Wla)	Wla	4,399,200
Mill residues (Sawdust) -Portion of sawlog (Wl) volume in the sawmill residues (Wls)	Wls	659,880
Trimming (Portion of sawlog (Wl) volume in the trim residues (Wlt))	Wlt	439,920
Pulp wood	Wp	9,898,200

Table 4
Cost and GHG emission of the saw milling.

	Energy input (kWh/T)	GHG (kg/T)	Cost ($/T)
Re-saw, Edging and trimming	48.8	1.2	1.66
Drying	53.8	1.3	9.6
Planning	36.4	0.9	2.4
Total	139	3.3	18.26

Table 5
Cost and GHG emission of the biorefinery.

	Energy input	GHG (kg//DT)	Cost ($/DT)
Chipping	2 (L/DT)	5.4	37.2
Fine Milling	2132 (kWh/DT)	51.2	92.2
Amorphization	1739 (kWh/DT)	41.7	76.6
Saccharification	228 (kWh/DT)	5.5	80.5
Total	2 (L/DT) 4099 (kWh/DT)	98.4	286.5

Table 6
Cost and GHG emission of the pellet mill.

	Energy input (kWh/T)	GHG (kg/T)	Cost ($/T)
Pelletization	19.3	0.5	14.5
Drying	19.6	0.5	12.2
Separation	7.4	0.2	3.3
Total	46.3	1.1	30

For instance, the production of one dry tone sugar through biorefinery is equal to $376, while the sugar production from sugar cane costs $590 (Cheng et al., 2019). In this regard, Cheng et al. (2019) came to the conclusion that the cost range of the production could vary between 220 and 550 $/T for biorefinery sugar (Cheng et al., 2019). For pellet production from forestry residue, Mobini reported 101 $/T for production cost and 1.22 for CO2eq (Mobini, 2015). The cost and GHG of all productions through forestry process are lower than their classic ways of productions.

As shown in Table 8, upstream stages are the largest contributors to the overall GHG and cost of lumber and pellet products. As shown in our previous publication (Shadbahr et al., 2021), transportation distances have a significant impact on the upstream stage. We have showed that the biorefinery size requires longer transportation distances and thus increasing GHG and cost. In the case of the sugar unit, the upstream logistics have relatively lower impact. Other parameters that could affect cost and GHG emission include the relative composition of different wood fiber streams, and the residue amounts from sawmilling and saccharification stages. To assess the impact of these parameters on the sugar unit performance, further field survey is required to assess the range of tree species and residues amount and quality at different process units. However, we don't expect variations of these parameters will have a significant impact.

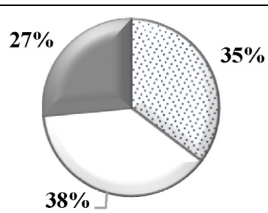
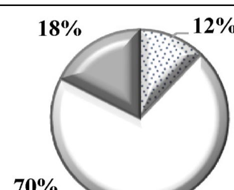
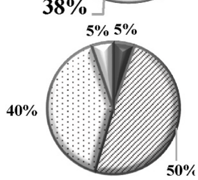
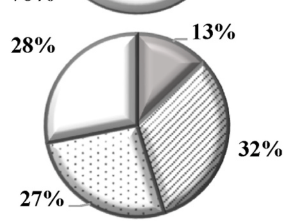
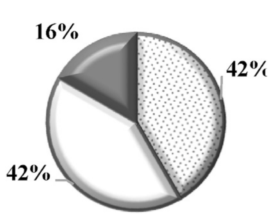
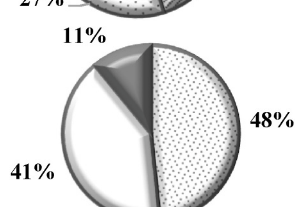
Table 8
Total cost and GHG emission of products.

Product		Upstream	Mid-stream	Total
Lumber	Cost ($/T)	89.76	18.26	108.02
	GHG (kg/T)	0.05	3.3	3.4
Sugar	Cost ($/DT)	89.76	286.5	376.26
	GHG (kg/DT)	0.05	98.3	98.4
Pellet	Cost ($/T)	89.76	30	119.76
	GHG (kg/T)	0.05	1.1	1.2

Table 9
Comparison of the cost and GHG of the work with baselines.

Product	Impact factor	This Work	Baseline
Lumber	Cost ($/T)	108.02	400
	GHG (kg/T)	3.4	242- 255 (Bergman et al., 2014b) (Maureen et al., 2010)
Sugar	Cost ($/DT)	376.26	590
	GHG (kg/DT)	98.4	300 (Rein, 2010)
Pellet	Cost ($/T)	119.76	250
	GHG (kg/T)	1.2	1.7 1.7 (Drax Annual Reports, 2013)

Table 7
Cost and GHG emission breakdown of the products.

	GHG emission	Cost	legend
Lumber			Re-saw, Edging and trimming Drying Planning
Sugar			Chipping Fine Milling Amorphization Saccharification
Pellet			Pelletization Drying Separation

5. Conclusions

This study evaluated different bio-based products pathways from the life cycle perspective and covered the environmental and economic aspects of three product lines (lumber, sugar, and pellet) using the same woody feedstock. The ranking of products based on assigned biomass ratio of each unit and the corresponding cost and embodied carbon attribution is fulfilled in the current study.

According to results obtained from the case of wood fiber production systems for a facility located in Pontiac region (Quebec, Canada), the lumber production costs is the cheapest among the other two products, followed by wood pellets. In terms of GHG emission, pellet production has the lowest carbon intensity which is approximately one third of lumber CO2 emission, so it is recommended to get more public and private investment in this area. In the process of sugar production, the highest CO_2 is emitted. The cost and GHG of all productions through forestry process are lower than their classic ways of productions.

Although the proposed framework and the obtained results are developed for a specific area with certain geographical and biomass characteristics, the approach can be applied in other regions with different specifications in terms of different biomass feedstock, amount of biomass, various harvest intensities, lignin content, and different scales. The main focus of this study is on all parts of forestry process but the proposed supply chain analysis can be adjusted for forest residues which can be more applicable for some other regions with different forestry residues like northern Quebec.

Credit author statement

Zahra Vazifeh, Methodology, Formal Analysis, Investigation, Writing, Validation.**'** **Farid Bensebaa**, Conceptualization, Methodology, Formal analysis, Investigation, Original draft, Validation, Review & Editing, Supervision, Project Funding and Management. **Jalil Shadbahr**, Formal Analysis, Review & Editing; **Giovanna Gonzales-Calienes**, Project Management, Review & Editing, **Fereshteh Mafakheri**, Supervision, Review & Editing. **Marzouk Benali**, Conceptualization, Review & Editing, **Mahmood Ebadian**, Review & Editing, Supervision, Validation. **Pierre Vézina**, Conceptualization, Investigation, Data collection, Review & Editing.

Declarationof competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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