IMPACT OF HARVESTED WOOD PRODUCTS CONSUMPTION STRATEGIES ON BRITISH COLUMBIA'S GREENHOUSE GAS EMISSIONS

by

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ABSTRACT

Keeping global temperature increases to below 2 °C will require reducing emissions and enhancing sinks and forest product uses can contribute. This research quantitatively compared the greenhouse gas (GHG) emission consequences of various harvested wood products (HWPs) utilization and export strategies for British Columbia's (BC) bioeconomy.

A state-of-the-art model, MitigAna, was developed to enable scenario-based mitigation analysis for HWPs with modules calculating substitution benefits and cascading uses. Timber construction and wood-based biofuels were identified as important contributors to GHG mitigation. Construction was the most climatically efficient utilization of HWPs because of its longer carbon storage and larger displacement factor than other applications. However, BC does not currently have sufficient international market access to fully realize the mitigation potential of a construction-focused bioeconomy, whereas available biofuel displacement markets would be sufficient to provide promising substitution benefits if technology to produce biofuels from woody biomass becomes available at a commercial scale.

GHG mitigation can be achieved by promoting wood buildings for future construction and shifting biomass supply from short-lived exports, such as pulp and wood pellets, to biofuel production, and mandating that these biofuels displace fossil fuels. This strategy would mitigate on average 17.4 $MtCO_2e\ year^{-1}$ between 2016 and 2050, which is equivalent to about 34% of BC's 2050 reduction targets. This would involve building the same floor area as at present, but the domestic market share of timber construction would need to double at the expense of concrete and steel. Redirecting biomass feedstock from exported pulp and wood pellets, 4.4 billion L $year^{-1}$ "drop-in" biofuels would be produced, equivalent to 50% of the energy demand in BC's transportation sector. This strategy may be a promising pathway for BC to achieve significant decarbonization in the transportation sector. However, if international collaborations on future wood buildings were in place, BC's HWP sector could make a maximum global mitigation contribution of 66 $MtCO_2e\ year^{-1}$. This indicates that potential conflict exits between BC-specific benefits and maximizing the global GHG mitigation outcome. International policies and accounting rules can influence the desired global mitigation outcomes.

LAY SUMMARY

This research informs British Columbia's greenhouse gas emission reduction polices by identifying climatically efficient utilization strategies of its forest resources. It evaluated whether the province's forest sector could be more domestic or export-oriented and which forest product uses were most climate-friendly.

The research determined the emission consequences of different wood utilization strategies compared to a business-as-usual baseline. Emissions were estimated using a complex model that tracked carbon flows in wood products from harvest until their release to the atmosphere.

Major emission sources and potential reduction contributors in the wood products sector were identified and quantified. This work developed a bioeconomy vision that combined timber construction and transportation biofuels that could contribute 34% of the province's 2050 emission reduction target. However, if international collaborations on future wood buildings were in place, BC's harvested forest biomass could contribute up to four times greater emission reductions to the global mitigation effort.

PREFACE

This thesis is the original work of the author, Sheng Hao Xie, and to the best of the author's knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

All research work reported in this thesis was designed, modeled, analyzed and interpreted by the author under the supervision of Dr Paul McFarlane and Dr Werner Kurz. Both supervisors provided meaningful suggestions to the design, modeling and revision of all chapters contained in the thesis.

Chapter 3 is a version of a manuscript that will be submitted for publication, titled *Inward- versus Outward-Focused Bioeconomy Strategies for British Columbia's Forest Products Industry: A Carbon Storage and Emission Perspective*. I planned, conducted the model run, analyzed the results, and drafted the manuscript. Werner Kurz and Paul McFarlane helped with the planning, design, data interpretation and writing of the manuscript.

Chapter 4 is a version of a manuscript that will be submitted for publication, titled *Substitution Benefits of British Columbia's Forest Products for Greenhouse Gas Mitigation*. I planned, designed, conducted the data analysis, and drafted the manuscript. Werner Kurz and Paul McFarlane helped with the planning, design, data interpretation and writing of the manuscript.

Chapter 5 is a version of a manuscript that may be submitted for publication, titled *Forest Sector Mitigation Consequences of Cascading Uses of British Columbia's Postconsumer Wood Products*. I planned, conducted the model run, analyzed the results, and drafted the manuscript. Paul McFarlane helped with the design. Werner Kurz and Paul McFarlane helped with data interpretation and writing of the manuscript.

Chapter 6 is a version of a manuscript that will be submitted for publication, titled *A Vision for the BC Forest Sector that Combines Mass-timber Construction and Biofuel Production to Contribute to Domestic Greenhouse Gas Emission Reduction Targets*. I planned, designed, conducted the model run, analyzed the results, and drafted the manuscript. Werner Kurz and Paul McFarlane helped with the data interpretation and writing of the manuscript.

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List of Abbreviations, Acronyms and Symbols

AE	avoided emissions
ALL_CONS	scenario label: all forest biomass manufactured to construction materials
ALL_FUEL	scenario label: all forest biomass as feedstock for renewable fuel
ASMI	Athena Sustainable Materials Institute
BASE	scenario label: the business-as-usual baseline
BC	the province of British Columbia in Canada
BCFLNRO	BC Ministry of Forests, Lands and Natural Resource Operations.
BCFLNRORD	BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development
C	carbon
CBMF-HWP	Carbon Budget Modeling Framework for Harvested Wood Products
CCAA	Climate Change Accountability Act
CLT	cross laminated timber
CMP	Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol
COP	Conference of the Parties
CORRIM	Consortium for Research on Renewable Industrial Materials
DF	displacement factor
EBD	Environmental Building Declaration
EU	European Union
FEA	Forest Economic Advisors
FII	Forest Innovation Investment Ltd.
FPAC	Forest Products Association of Canada
FPI	FPInnovations
GGRTA	GHG Reduction Targets Act
GHG	Greenhouse gas
GluLam	glue laminated timber
$GtCO_2e$	giga tonnes of carbon dioxide equivalent
HHV	high heating value
HTL	hydrothermal liquefaction
HWPs	harvested wood products

ICT	information and communication technologies
IN_CONS	scenario label: inward-focused, increase domestic market share of wood-frame construction
INDC	Intended Nationally Determined Contribution
IN_FUEL	scenario label: inward-focused, prioritize renewable fuel feedstock
IN_PCF	scenario label: inward-focused, population-driven, construction-dominated biofuel-subordinated
IN_POP	scenario label: inward-focused, demand increase driven by population growth
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle assessments
LVL	laminated veneer lumber
MDF	medium density fibreboard
MSP	minimum selling price
Mt	mega tonnes
$MtCO_2e$	mega tonnes of carbon dioxide equivalent
NAFTA	North American Free Trade Agreement
OSB	oriented strand board
OSL	oriented strand lumber
OU_CN	scenario label: outward-focused, prioritize export to China
OU_CONS	scenario label: outward-focused, prioritize export to US and other markers for constructions
OU_EU	scenario label: outward-focused, prioritize export to EU for energy
PICS	Pacific Institute of Climate Solutions
RCP	Representative concentration pathway
StatCan	Statistics Canada
t½	half-life
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
WIDC	Wood Innovation and Design Centre
α	shape parameter for the Gamma distribution

β	scale parameter for the Gamma distribution
τ	average service life

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Lastly, I am grateful to my family for their understanding and support.

To my parents, Sheryn and Janie

1 Introduction

1.1 Overview

The recent warming of our climate system is unprecedented, with the atmospheric concentration of carbon dioxide (CO_2), the main driver of climate change, surpassing its record high levels over the last 4 million years [1, 2]. Emissions from anthropogenic fossil fuels and land-use changes have been the dominant causes of increased CO_2 concentrations [1]. As of February 2019, 185 of the 197 Parties that attended the United Nations (UN) Climate Change Conference (COP 21/CMP 11) in 2015 have ratified the Paris Agreement with the goal of keeping the global average temperature rise in this century to well below 2 °C, committing to limiting the increase to 1.5 °C and reaching net zero emissions in the second half of this century [3]. According to the representative concentration pathways (RCPs), achieving this target requires the atmospheric CO_2 concentration to peak at about 450 ppm by 2030 and decline thereafter (RCP2.6 [1]). Within this context, 165 Parties have submitted their Intended Nationally Determined Contributions (INDCs) which outlined their post-2020 climate actions to realize this target [4]. The Government of Canada has ratified a target of 30% emission reduction compared to the 2005 emission levels by 2030 [5, 6]. The Canadian Province of British Columbia (BC) has committed to reducing its greenhouse gas (GHG) emissions to 40%, 60% and 80% below its 2007 levels by 2030, 2040 and 2050 respectively [7]. Despite these pledges, Canada has previously missed its Kyoto Protocol target of a 6% reduction by 2012 and withdrew from the Kyoto Protocol in 2011 [8]. In addition, although BC has achieved its 2012 targets, the province's emissions have been increasing ever since and are projected to miss the 2020 target of 33% reduction that was previously legislated [9–11]. Achieving GHG reduction commitments is more pressing than ever and requires the joint effort of all sectors.

The forestry sector has an important role to play in climate change mitigation. This sector can greatly influence the climate due to the sector's ability to act as a carbon sink or source. Forests absorb CO_2 from the atmosphere through photosynthesis and can create a carbon pool by storing carbon in all components of a tree, in the soil and in harvested wood products (HWPs). Forests absorb more than a quarter of the annual global anthropogenic carbon emissions [12–19]. The production of wood products after harvesting incorporates much of this carbon into the HWPs consumed by society. The carbon stock in HWPs has been estimated to be about 10% of aboveground biomass of forests in the United States (US) and the European Union (EU) [20–22].

Although it varies depending on ecosystem type, the ability to sequester carbon can decrease in aging forests [23, 24]. Large scale natural disturbances may release substantial amounts of carbon into the atmosphere and forests may then become net carbon sources [25, 26]. In a sustainably managed landscape, carbon transfers from the forest, initiated by harvesting roundwood, are balanced over time by the carbon removals from the atmosphere caused by regrowth [24, 26, 27]. Therefore, if the forests that produce HWPs are sustainably managed, meaning that the harvest volume is equal to or less than the mean annual increment (minus natural disturbances) over the long term, then this forest-HWP-in-use system will be capable of creating stocks of carbon with the annual net carbon sequestration amount equaling or above the net annual increase in the size of the HWP pools. As long as the inflow to the HWP pools exceeds the outflow from the HWP pools, these pools will act as carbon sinks and pools with long-term carbon inputs that are greater than the outputs have the potential to act as long-term carbon sinks.

Greenhouse gas emission reduction also can be realized by substituting HWPs for emission-intensive materials and fuels [28]. Forest biomass is a renewable resource and the forest-HWP system creates two-way carbon fluxes: sequestration through photosynthesis and emissions through decomposition and combustion. Fossil fuels are nonrenewable and can only create a unidirectional carbon emission flux. In general, wood-based products and biofuels are considered “carbon leaner” than many other functional equivalencies and the substitutions can provide climate benefits [29]. Fossil fuel consumption during HWP manufacturing is lower than for non-wood products (e.g., metal, concrete, brick and plastic), especially when milling residues are burnt to replace coal and natural gas to produce heat and steam for the manufacturing process [30]. In addition, replacing concrete with wood can avoid process emissions from cement calcination [31, 32]. Therefore, the forest-HWP system has several advantages in contributing to GHG emission reduction.

British Columbia has 55 million hectares (ha) of forested area and a population of less than 5 million people. The forest area per capita is over 11 ha per person, which provides GHG mitigation opportunities available to few other jurisdictions [33, 34]. For decades, BC’s forests have provided society with energy and materials for shelter, furniture, communication, information recording, packaging and hygiene. Forest products play an important role in BC’s bioeconomy. In 2016, BC emitted 62 million tonnes of carbon dioxide equivalents per year ($MtCO_2e$ $year^{-1}$) from sectors other than forestry [10] and harvested 66 million cubic meters of biomass under bark per year (Mm^3 u.b. $year^{-1}$) (i.e., approximately 60 $MtCO_2e$ $year^{-1}$) from the forest [35]. Therefore, the utilization of the harvested biomass has had, and will continue to have, a significant impact on BC’s emission profile and a quantitative assessment of how best to utilize this biomass to reduce provincial GHG emissions is warranted.

Nations such as Finland and Sweden that possess similar forest resources to BC have developed wood-based bioeconomy strategies to create synergies between economic growth and climate change mitigation [36, 37]. When this research was started, BC did not have a clearly defined bioeconomy strategy other than an advisory committee report that summarizes bioeconomy related activities in the province and around the world [38]. As a consequence of the reduction in growing stocks from the impacts of the Mountain Pine Beetle and large-scale forest fires in recent years [34, 39], BC's current lumber- and pulp-dominated forest industry is facing major challenges caused by the reduction in timber supply and difficult market conditions [40]. Sawmills and pulp mills in BC are experiencing extended production curtailments and shutdowns [41]. The growing global demand for renewable bioproducts requires a structural transformation of BC's traditional forest industry and the value-adding wood products need to be diversified and extended to increase BC's economic and social performance and competitiveness in international markets. While a practicable HWP-based bioeconomy strategy must be economically viable and rejuvenate the rural communities, these issues are beyond the scope of this study and addressed by other analyses (e.g., [42]). The focus of this thesis is climate change mitigation. This chapter outlines the research objectives and presents a review of the relevant literature.

1.2 Research objectives

This study has four objectives:

- to identify feasible strategies and important policy levers using harvested wood products to help reduce BC's net GHG emissions;
- to refine the existing Canadian and BC HWP models to a state-of-the-art, BC centric and multiple jurisdictional HWP carbon dynamics model (Ch. 2);
- to forecast quantitatively the mitigation benefits of various HWP production and utilization strategies achieved through carbon storage in HWPs (Ch. 3 and 5) and by avoiding emissions through product substitution (Ch. 4); and
- to demonstrate quantitatively the differences between domestic- versus export-focused strategies for HWP uses and their implications for BC's ability to meet domestic GHG emission reduction targets (Ch. 3, 4 and 6).

1.3 RESEARCH HYPOTHESIS

The hypothesis of this research was that BC could achieve greatly enhanced GHG emission reductions by restructuring its forest bioeconomy.

1.4 BACKGROUND

Conducting mitigation analyses to evaluate alternative mitigation strategies requires an understanding of greenhouse gas inventories, emission targets, the current status of the forest industry, available strategic options, and accounting approaches to assess mitigation outcomes. Quantitative models may then be developed to evaluate options that are worth pursuing based on their mitigation benefits, requisite policy levers, and associated risks and uncertainties. This section is a literature review addressing these topics.

1.4.1 GREENHOUSE GAS INVENTORY OF BRITISH COLUMBIA

Between 1990 and 2016, British Columbia's average *reported* annual emissions were 62 $MtCO_2e$ $year^{-1}$ [10]. The reported emissions were relatively consistent from 1990 to 2016 with a standard deviation of only 3.9 $MtCO_2e$ $year^{-1}$ (Tbl. 1). BC's annual emissions in 2016 were also 62 $MtCO_2e$ $year^{-1}$ and Fig. 1 shows the breakdown by reporting sectors at this time [10]. Almost 80% of the GHG were emitted by the energy sector, which includes transportation and stationary combustion. If categorized by economic sector, 40% (25 $MtCO_2e$) were emitted by industry, 40% by the transportation sector, 13% (8 $MtCO_2e$ $year^{-1}$) by the building sector, 7% by waste and deforestation [43].

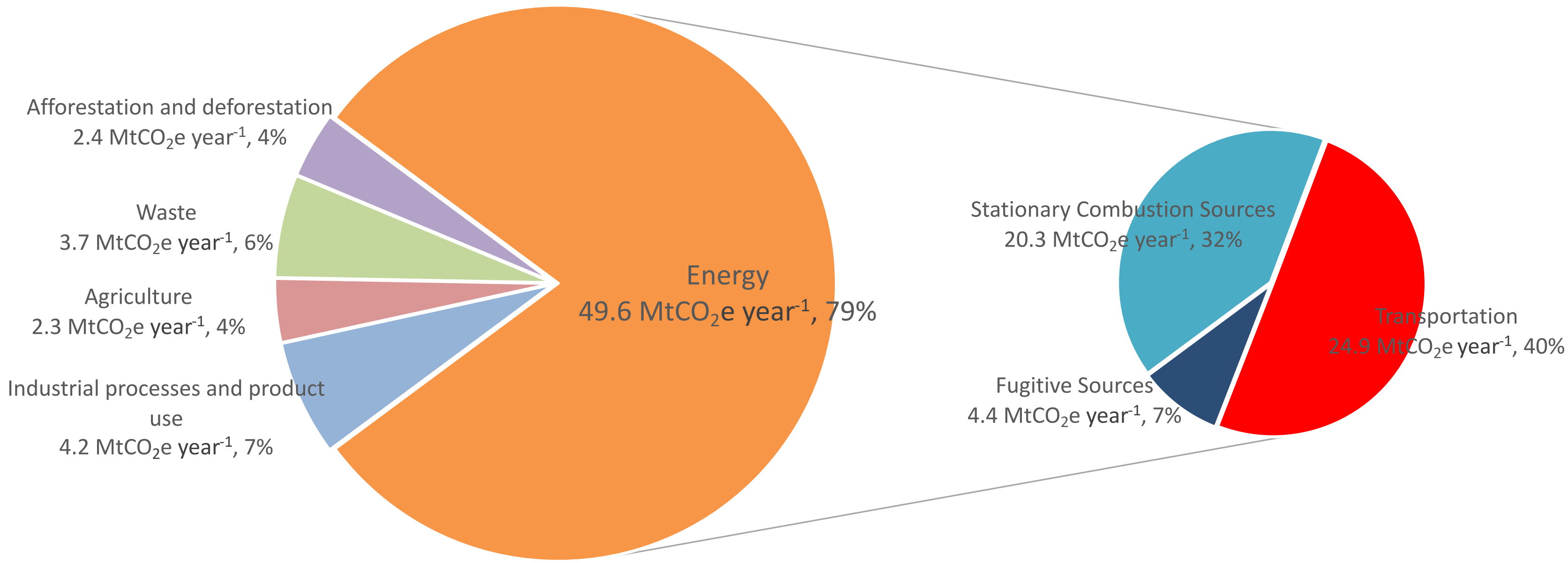

Figure 1. British Columbia 2016 greenhouse gas emissions by reporting sectors [10].

British Columbia's reported emissions did not include emissions and sinks in several other land-use categories (i.e., forest, cropland, wetland, grassland and settlement managements. Tbl. 1). Sinks associated with settlement management were relatively consistent with an average of -500 ktCO_2e year^{-1} and a standard deviation of 3 ktCO_2e year^{-1}. Emissions from cropland, wetland and grassland management were relatively insignificant compared to other sectors, although the annual values can vary substantially year-over-year as indicated by their standard deviations compared to their averages (Tbl. 1).

Table 1. Other land use average emissions and sinks (negative values) and standard deviations from 1990 to 2016 that were not included in BC's reported total emissions [10].

GHG categories	Average emissions (MtCO_2e year^{-1})	Standard deviation (MtCO_2e year^{-1})
Reported emissions	62.2	3.9
Emissions/sinks that were not included	-7.3	
Forest management	-7.0	47.9
Forest growth minus decay	-68.1	34.4
Slash pile burning	6.2	1.8
Wildfires	15.6	19.5
Harvested wood products	39.4	4.4
Cropland management	0.093	0.056
Wetland management	0.074	0.028
Grassland management	0.048	0.067
Settlement management	-0.5	0.003

Emissions from forest management were consistent before 2003 but have substantial variations year-over-year after that, due to natural disturbances such as insects and fires which severely reduced the net carbon sequestration of BC's forest (Fig. 2A and Tbl. 1). Cumulatively between 1990 and 2016, BC's forests had been a slight carbon sink of 189 MtCO_2e (i.e., on average 7 MtCO_2e year^{-1}, Fig. 2B). The latest provincial forest inventory available when this research was conducted was for 2016 but it is estimated that fire emissions will continue to rise, and BC's forest will cumulatively become a slight source when 2017 and 2018 data become available. Emissions from HWPs (on average 39.4 MtCO_2e year^{-1}) have been consistent and were cumulatively the largest component of BC's forest sector emissions. They accounted for 64% of the forest sector emissions between 1990 and 2016 and were cumulatively twice the emissions from fires (Fig. 2B).

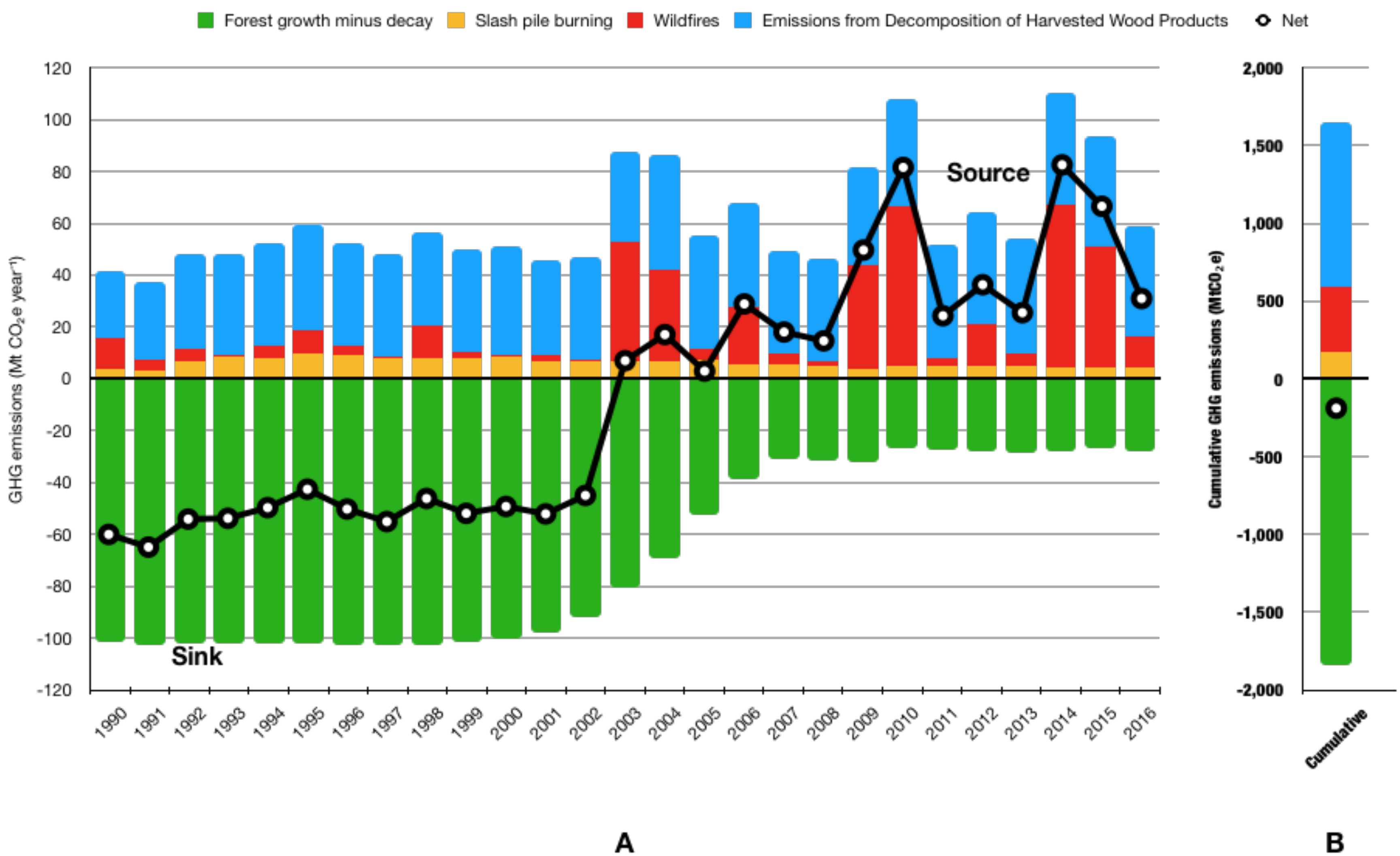

Figure 2. Annual (A) and cumulative (B) greenhouse gas emissions from BC's forest sector [44].

The goal of reporting annual GHG emissions and removals is to quantify the impact of anthropogenic activities on the atmosphere, identify the drivers of emissions, inform mitigation strategy development and quantify the effectiveness of the mitigation activity [26]. Wildfires are an important element of BC's present emission profile and are likely to continue to be so in the future. However, the large yearly variability of natural disturbances, such as wildfires, can strongly mask the effects of human forest mitigation activities. The Intergovernmental Panel on Climate Change (IPCC) acknowledged the challenges for countries with large areas subjected to natural disturbances (e.g., Canada, Russia and Australia) [45]. Kurz et al. developed an approach to separate anthropogenic and natural disturbance components [26]. Although a provincial level quantification using this approach is not published, anthropogenic activities in Canada's managed forests have been estimated to remove 20 $MtCO_2e$ $year^{-1}$ in 2016 (included 130 $MtCO_2e$ $year^{-1}$ emissions from HWPs), with natural disturbances accounting for emissions of 98 $MtCO_2e$ $year^{-1}$ resulting in net emissions of 78 $MtCO_2e$ $year^{-1}$ [34, 46].

This research sought to quantify and identify the anthropogenic mitigation potentials using harvested wood products through various inward- or outward-focused utilization scenarios in BC.

1.4.2 GHG EMISSION REDUCTION PLANS RELATED TO HARVESTED WOOD PRODUCTS

BC is a major wood products exporter with 90% of the manufactured forest products exported to the international markets in 2016, representing 36% of BC's commodity exports (see Section 1.4.4 Forest products manufacturing value chain). Under the current internationally agreed "production approach" GHG emissions reporting rule, BC is responsible for reporting emissions arising from biomass that was harvested in BC, regardless of where in the world the HWP emissions occur [47, 48]. Consequently, the emissions reduction plans established by Canada, BC and importers of BC wood may all have impacts on BC's bioeconomy and emission profile. This section reviews the GHG emission reduction plans of these jurisdictions.

1.4.2.1 Canada

Between 1990 and 2016, Canada emitted approximately 738 ~ 890 $MtCO_2e$ $year^{-1}$, contributing about 2% of global GHG emissions [49]. In 2016, the emissions per capita were 19.4 t $person^{-1}$ which ranked Canada within the top 20 GHG emitting countries on a per capita basis [46]. Canada's emissions have increased by 5% since the ratification of the Kyoto Protocol in 2005 [50]. In 2015, Canada ratified the Paris Agreement and submitted the intended nationally determined contribution (INDC) of a GHG emissions reduction of 30% below its 2005 level by 2030 which equates to a reduction in annual emissions to less than 523 $MtCO_2e$ $year^{-1}$ (i.e., a reduction of 219 $MtCO_2e$ $year^{-1}$

from the 2016 emissions level of 742 $MtCO_2e$ $year^{-1}$) [5]. Three sets of measures are intended to be used to meet this target [51]:

- 89 $MtCO_2e$ $year^{-1}$ (41%) by regulations, *provincial measures* and international cap-and-trade credits;
- 86 $MtCO_2e$ $year^{-1}$ (39%) by measures in the Pan-Canadian Framework on Clean Growth and Climate Change (i.e., the federal climate action plan);
- 44 $MtCO_2e$ $year^{-1}$ (20%) by additional measures in public transit, green infrastructure, technology and carbon storage in forests, soils and wetlands.

The Pan-Canadian Framework outlined carbon pricing as the primary mitigation option with complementary actions from the electricity, built environment, transportation, industry, forestry, agricultural and waste sectors [51]. The plan established a nation-wide carbon price with a floor price on carbon emissions of 10 dollars t^{-1} by 2018 with a 10 dollars t^{-1} $year^{-1}$ annual increase until a ceiling of 50 dollars t^{-1} will be reached by 2022 [51]. However, the provinces of Saskatchewan and Manitoba have not committed to the Pan-Canadian Framework. Additionally, the provinces of Ontario, Saskatchewan and Alberta have filed court appeals against the federal carbon tax [52].

Canada's forest industry was the first industrial sector to voluntarily contribute to the federal government's climate targets. The Forest Products Association of Canada (FPAC) has pledged to remove 30 $MtCO_2e$ $year^{-1}$ from the Canadian forest products industry emissions by 2030 [53]. FPAC intended to achieve this target through maximizing forest carbon sinks, sequestering carbon in HWP, and reducing GHG emissions during manufacturing.

1.4.2.2 The province of British Columbia

In 2007, BC introduced the GHG Reduction Targets Act (GGRTA) that mandated a 33% of reduction compared to the 2007 emission level of 64 $MtCO_2e$ by 2020 (i.e., a reduction of 21 $MtCO_2$ $year^{-1}$) and an 80% reduction by 2050 (i.e., a reduction of 51 $MtCO_2e$ $year^{-1}$) [11]. Following the GGRTA, the province announced the Climate Action Plan in 2008 [54], the Climate Action for the 21 Century in 2010 [55] and the Climate Leadership Plan in 2016 [56]. Meanwhile, BC introduced a carbon tax starting at 10 dollars t^{-1} in 2008, increasing by 5 dollars t^{-1} $year^{-1}$ until 2012 when it reached 30 dollars t^{-1} [57].

In 2018, the province reported that the 2016 emissions were 62 $MtCO_2e$ $year^{-1}$, up by 1.5% from 2015 and that it is unlikely to meet the GGRTA's 2020 target. Therefore, the province replaced GGRTA with the new Climate Change Accountability Act (CCAA), removed the 2020 target [58], and added two new intermediate reduction targets of 40% and 60% below the 2007 level by 2030 and 2040, respectively (i.e., a reduction of 25 and 38 $MtCO_2$ $year^{-1}$, respectively) [7]. In addition, in 2018 BC increased carbon tax to 35 dollars t^{-1} and set a 5 dollars t^{-1} $year^{-1}$ increase until 2021 when it will reach 50 dollars t^{-1} to match the price specified in the Pan-Canadian Framework [59]. The increased carbon pricing is expected to achieve an emissions reduction of 1.8 $MtCO_2e$ $year^{-1}$ by 2030 [60]. In association with the CCAA, BC released a new climate action strategy, the CleanBC plan [60]. This plan described key actions in clean transportation (targeting a reduction of 6 $MtCO_2e$ $year^{-1}$), net-zero energy buildings (2 $MtCO_2e$ $year^{-1}$ reduction), clean industrial operations (8.4 $MtCO_2$ $year^{-1}$ reduction) and waste management (0.7 $MtCO_2e$ $year^{-1}$ reduction) by 2030 (Fig. 3). Including the forecasted carbon tax impacts, these actions are projected to achieve a reduction of 18.9 $MtCO_2e$ $year^{-1}$ by 2030 which is about 75% of the CCAA 2030 target.

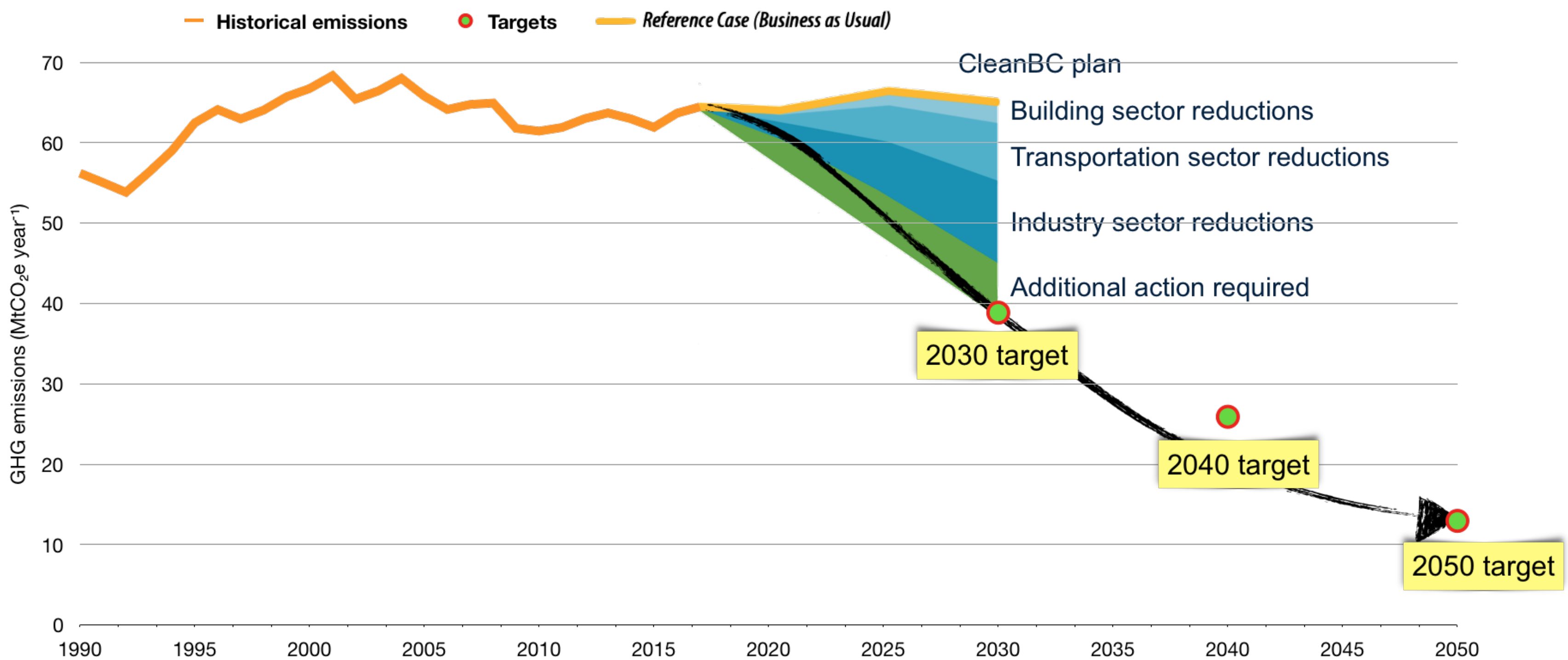

Figure 3. Emissions and targets of British Columbia (sectors other than forest management) [7, 44, 60].

Harvested wood products may contribute to multiple initiatives outlined in the CleanBC plan. The plan sets a renewable fuel production target of 650 million liters by 2030 which is about 8% of the current energy demand (334.45 PJ) in the transportation sector, and identified harvested biomass and residues as major potential feedstocks for biofuel production. However, there are several technological and economical barriers that need to be overcome before wood-based renewable transportation biofuel can be commercialized [61] (see Section 1.4.5.1.2.2 Wood-based “drop-in” biofuel). It is also unknown whether BC’s biomass supply is sufficient for this renewable fuel production target. The specific mitigation benefit that this initiative can realistically achieve is also unknown, and these topics will be quantified by this research. The plan also targeted that all new constructions in BC will be “net-zero energy ready” (i.e., 80% more energy efficient than the current level) by 2032. BC has 50 million ha of certified forest land, more than any single country in the world [62]. 75% of BC’s timber harvest is from certified sustainably managed forest [63]. HWPs manufactured from sustainably managed forests are less emission intensive on a life cycle basis than other common building materials [30]. However, a detailed quantification of this mitigation benefit is missing. This research will quantify the potential mitigation benefit of using BC wood as construction materials.

Harvested wood products may also be able to contribute to the remaining 25% of the CCAA 2030 target where actions were not detailed in the CleanBC plan but the potential areas were described. Two related topics identified were waste reduction and the adoption of a circular economy [60]. This research will explore the mitigation benefit of an important option in the circular economy related to HWPs, the cascading uses of wood.

1.4.2.3 European Union

The European Union (EU) has set ambitious GHG reduction targets. Their 2020 climate and energy package mandated a 20% emission reduction compared to the 1990 levels [64]. To help achieve that target, the energy component of the package required a 20% contribution of renewables to energy consumption and a 20% increase in energy efficiency [65]. The 2030 package mandated a 40% emission reduction with 32% contribution of renewables and 32.5% increase in energy efficiency [66]. Their long-term carbon neutral vision outlined a road map towards an 80% emissions reduction by 2050 [67].

The EU has been actively pursuing these targets and claimed to be on track to overachieving the 2020 targets [68]. The EU’s key climate action plans are through the adoption of the EU emission trading system (ETS) which covers 45% of the EU’s GHG emissions [65]. The ETS is a “cap and trade” system that aims to make fossil fuels unaffordable and achieve the targets such as an increased renewable share. The EU's other action plans include: establishing effort sharing legislation and taking measures such as fuel switching in transportation; increasing efficiency in heating and cooling, and conversion of livestock manure to biogas [69]; and supporting low carbon technologies through funding and financing [66].

One of the most relevant planned actions for BC and Canada is the EU's increasing share of renewables in energy consumption. Bioenergy consumption in the EU is expected to increase by 80% by 2050, which may lead to a significant expansion of its demand for wood pellets [67]. A scenario analysis estimated that by 2050, 20 Mt of the EU's pellet imports will come from BC [70, 71], which would have a substantial impact on BC's emission profile. Under international reporting rules, the country in which wood has been harvested must report emissions from wood products, including wood pellets, regardless of where in the world these emissions occur [47, 48]. Consequently, the emissions from burning the wood pellets exported by BC in the EU region would enable the EU to report reduced emissions in the energy sector but increase the reported HWP emissions in BC. At the moment, carbon accounting models in BC and Canada do not track GHG emissions from HWPs at the level of granularity that details the subdivided bioenergy types (i.e., different types of bioenergy uses are not separated) [10, 46]. Objective 2 and 4 of this research project will address and investigate the outcomes of various HWP export strategies for bioenergy and other product categories.

1.4.3 The forest-harvested wood products carbon cycle in British Columbia

The forest-harvested wood products system in British Columbia was a carbon sink prior 2003 but more recently may have acted as a carbon source (Fig. 2). Between 1990 and 2016, BC's forest absorbed an average of 68 $MtCO_2e$ $year^{-1}$ through photosynthesis minus decay, and emitted an average of 15.6 $MtCO_2e$ $year^{-1}$ back to the atmosphere through fires [10] (Fig. 4). Over the same period, harvest activities transferred an average of 65 $MtCO_2e$ $year^{-1}$ of biomass from the forest and converted it into various types of wood products [35, 39]. Decay and combustion of wood products released an average of 39 $MtCO_2e$ $year^{-1}$ back to the atmosphere, while an average of 26 $MtCO_2e$ $year^{-1}$ were stored in wood products used by society. Harvest, replanting and long term carbon storage in wood products can allow the forest to have space and time to regenerate while providing society with biomass resources. For centuries, human society has used this lignocellulosic material to meet its needs for energy, shelter, furniture, communication, information recording, packaging and hygiene [72]. If conducted correctly, sustainable forest management practices can maintain strong carbon sinks in the forest [73, 74]. In addition, wood products can further reduce emissions in other sectors by substituting for more emission-intensive materials, such as steel and concrete in the construction sector, and fossil fuels, such as gasoline and diesel in the transportation sector. BC's average emissions from the other sectors are 62 $MtCO_2e\ year^{-1}$ [10].

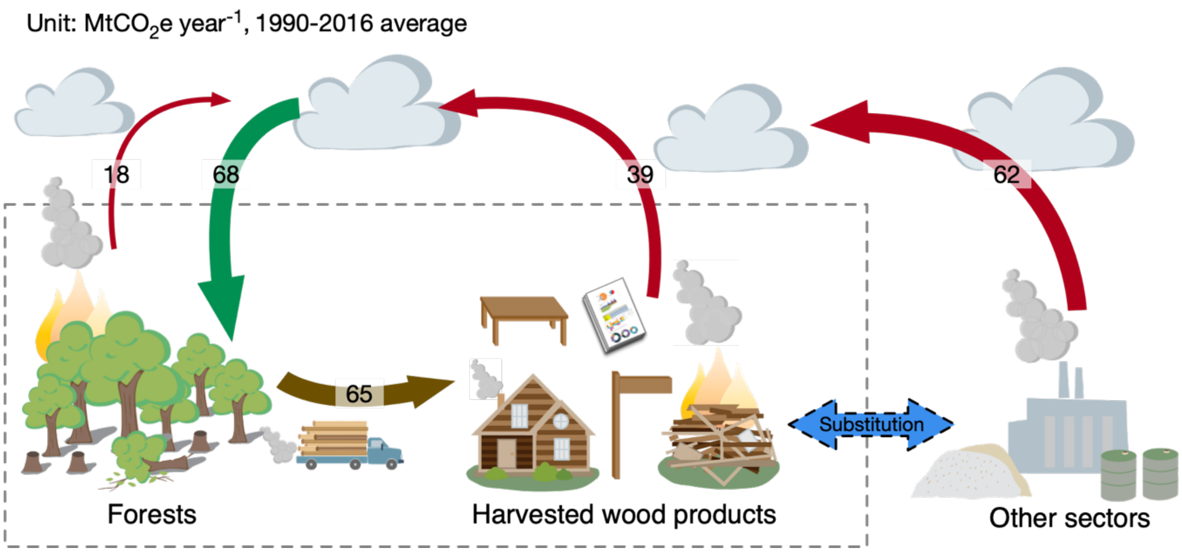

Figure 4. Forest-harvested wood products carbon cycle in British Columbia [10, 39].

1.4.4 *FOREST PRODUCTS MANUFACTURING VALUE CHAIN*

Fig. 4 only demonstrates a partial life cycle of harvested wood products. Because of the complexity of the wood products manufacturing value chain and end-of-life practices, this research needed to be constrained to the use phase. Any landfill-related issues were beyond the scope of this study, consistent with the way in which Canada's GHG Inventory is reported [46]. Several mitigation options can be identified along the wood products manufacturing value chain which would lead to increases or decreases of the sizes of the carbon flow arrows in Fig. 4. Alternative means of improving the climate efficiency of BC's forest sector, such as means of minimizing the emissions from pests, diseases and forest fires and mechanisms for increasing the CO_2 sequestration by forests are beyond the scope of this study but some of these issues are addressed in related studies of the PICS Forest Carbon Management Project [42].

In 2016, BC's timber harvest volume was 66 million cubic meters under bark per year (Mm^3 u.b. $year^{-1}$) which contains approximately 17 Mt $year^{-1}$ of carbon (or 60 $MtCO_2e\ year^{-1}$) [35], and 89% of the harvest volume came from provincial Crown land [75]. Consequently, through policy development, the provincial government can influence the structure of BC's future forest industry and in enhancing its climate change mitigation benefits. As a consequence of Mountain Pine Beetle reducing the growing stocks between 1999 and 2015 and large-scale forest fires between 2003 and

2018 [34], the timber supply is projected to continuously decline from 68 Mm^3 in 2016 to 55 Mm^3 in 2030 [75]. This indicates that the size of carbon transfer from the forest to HWPs in Fig. 4 will shrink for the next decades. The harvest volume is not expected to recover until 2070 [39].

As indicated in Fig. 5, in 2016, 42% of the harvested carbon was stored in solid and composite wood products [35]. Although only 17% of the harvested carbon ended up in the pulp and paper products, 20% of the harvested carbon was emitted through burning of black liquor, a by-product generated during kraft pulp production, which is burnt on-site to recycle chemicals and provide electricity and heat. BC's forest industry is dominated by lumber and pulp production. In 2016, BC produced 32 Mm^3 $year^{-1}$ of lumber and 5.4 Mt $year^{-1}$ of pulp [76]. Manufacturing sales for lumber and pulp were 6.5 billion dollars and 4.3 billion dollars in 2016, respectively, representing 43% and 28% of total wood products manufacturing sales [77].

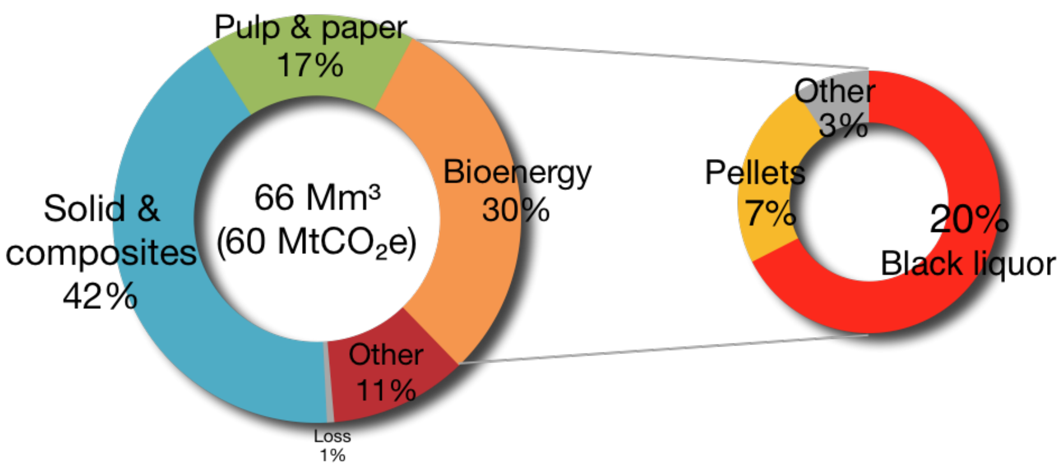

Figure 5. Average allocation of BC's harvested biomass in wood product commodities in 2016 (hog fuel of approximately 7.8 $MtCO_2e$ was not included) [35].

BC's current forest sector is export-oriented with 90% of the HWPs exported in 2016 [76]. The US is the largest export market for BC and has recovered steadily since 2009 (Fig. 6). In 2016, 59% of solid wood products and 19% of pulp and paper products manufactured in BC were shipped to the US, although these are significantly smaller shares compared to the pre-2009 period (i.e., 82% for solid wood and 24% for pulp and paper) [78]. China continued to be the second largest export market for BC since 2009 with 19% of the solid wood products and 47% of the pulp and paper products manufactured in BC shipped to China in 2016 (Fig. 6). The lumber export volume to China has declined since 2013 due to strong competition from Russia but pulp export remained relatively stable [79]. In 2016, 7% of the harvested biomass was converted to wood pellets (Fig. 5). Foreign demand for wood pellets increased 50% in 2016 [78]. The EU is the primary destination which consumed 1.58 Mt $year^{-1}$ of BC's wood pellets production (82%, Fig. 6).

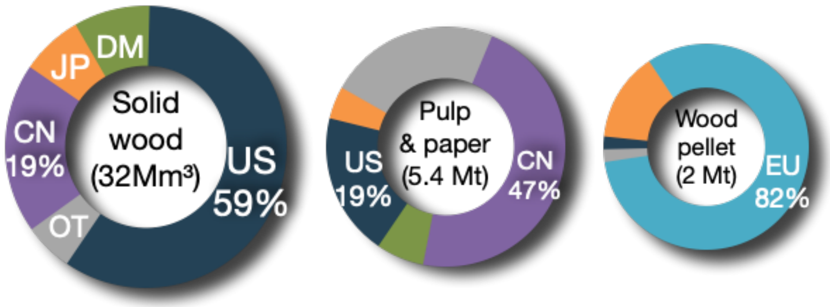

Figure 6. Average consumption partition of BC's harvested wood products by jurisdiction in 2016 (DM: domestic, BC wood consumed in BC and other provinces in Canada) [78].

Different markets consume BC's wood commodities for very different end-uses. For example, in North America, a majority of the lumber is used as structural material in constructions (Fig. 7). This type of applications usually has a service life of approximately 70~100 years (detailed discussion of service lives and end uses are in Ch. 2). In Canada, approximately 30% of the residential dwellings and 10% of the non-residential buildings are built with wood. BC's timber construction shares are larger than the rest of Canada at approximately 50% of residential and 25% for non-residential [80–91]. Whereas in China, most of the lumber is used as temporary construction material such as concrete casing with a service life of 0.5-2.5 years [92]. If BC's timber construction market penetration initiatives such as project demonstrations conducted by Canada Wood Group [83] can successfully shift the future wood utilization behavior in the foreign market, or if BC could create strong policy incentives to increase the market share of timber constructions in the domestic market and shift some of the short-lived exports to domestic long-lived uses, the size of the emissions from HWPs to the atmosphere in Fig. 4 would decrease. In addition, the substitution effect of wood material can contribute to the emission reduction of other sectors. Potential mitigation options are further explored in the next section.

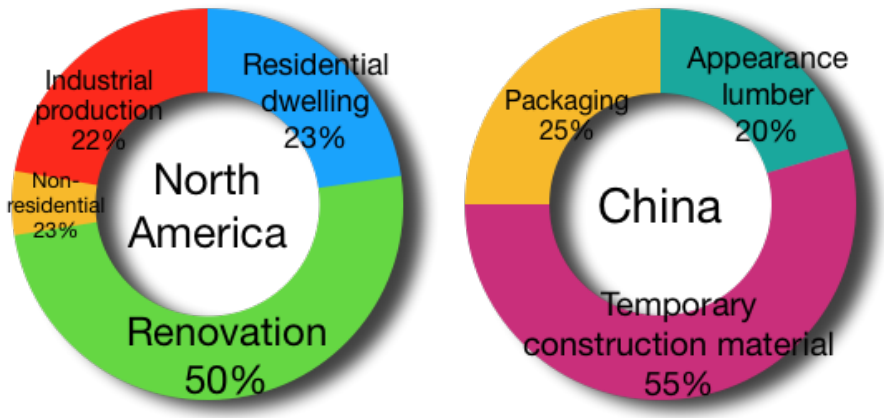

Figure 7. Estimated end use partitions of lumber in North America and China [81, 82, 84–92].

In 2016, BC's forest sector provided 141 thousand jobs (60 thousand direct employment) and generated a gross domestic production (GDP) of 13 billion dollars, representing 3.4% of BC's total GDP [93]. However, BC's export-oriented, lumber- and pulp-dominated forest industry is vulnerable. It relies on global forest product market conditions and is sensitive to foreign competition, trade policy and exchange rates [77, 94]. In 2019, BC's forest industry has experienced large scale sawmill and pulp mill production curtailments and shutdowns due to low lumber price and high log cost [40, 41]. Beetles and wildfires in recent years affected the volume of timber supply. Increased competition from the European lumber producers is probably influenced by the bark beetle outbreak in the Central Europe [95–97]. BC has a number of forest product dependent communities (e.g., Vavenby, Mackenzie and 100 Mile House) and the forest sector plays a key role in BC's rural socio-economic conditions. Any transitions in the structure of the forest sector will have socio-economic implications. The mitigation scenarios designed in this thesis recognize that the potential structural transformation may rejuvenate the rural communities but socio-economic analyses are beyond the scope of this work and these issues are addressed in other analyses (e.g., [42]).

1.4.5 HARVESTED WOOD PRODUCTS MITIGATION STRATEGIES

As illustrated in Fig. 4, harvested wood products play a key role in GHG emission reduction. Good utilization and trade strategies would contribute to the direct reduction of emissions from HWPs to the atmosphere, and through substitution effects, contribute to the reduction of emissions from other sectors. This section reviews the implications of different utilization and trade practices for the strategic development of BC's GHG mitigation options.

1.4.5.1 Utilization

The utilization of harvested forest biomass can be divided into two broad categories, material use and energy use.

1.4.5.1.1 Material use

The material use of woody biomass is an application that takes advantage of the mechanical properties of wood or its fiber, as opposed to treating wood as a fuel. Examples of material uses of wood include structural applications, furniture and paper. Innovative uses of chemical extractives from woody biomass may expand the boundary of this category, such as lignin glue applications. Like a piece of equipment or a tool, people usually have an expectation of the service time that a material use of wood should endure, as opposed to instantaneously oxidized during function realization. The various service life values of wood end uses are described in Ch. 2. This section reviews mitigation options of material use of wood.

1.4.5.1.1.1 Storage benefit

During the service phase of a wood product, the carbon is stored in the product and is not released to the atmosphere. Because this carbon was previously sequestered by the forest, the delay of carbon release provides a carbon storage benefit. If the HWP is used for long-lived applications, such as the structural component in a building, the carbon can be retained for many decades or in some cases even centuries. Longer carbon retention provides more time for the forest to regenerate and for society to develop advanced climate-friendly technologies. In addition, long-lived uses can make a dominant contribution to the potential HWP carbon storage magnitude and duration which would more effectively realize HWPs' ability to store carbon than short-lived uses. As an illustration of this point, the carbon pools as a function of time in Fig. 8 have been developed with a constant annual input of 1 $MtCO_2e$ $year^{-1}$ flow into various wood product end uses and commodities. The Gamma distribution retention pattern was used to demonstrate the US and Canadian residential dwellings and furniture with average service lives of 166, 110 and 38 years respectively [98–100]. The first order decay retention pattern was used to describe the behaviors of the sawnwood and paper pools with the IPCC default half-lives of 35 years and 2 years [47].

The half-life is the time it takes for a quantity of wood products to lose half of the initial amount [101]. The first order decay pattern can be solely defined by half-life [102] and therefore lead to its popular use in the literature as an indication of the longevity of product service life [47, 100, 103]. The service life is the time that an HWP is used by society before it is retired. The average service life is used to describe the mean time of a quantity of wood products used for a similar purpose before retirement. Depending on the decay pattern, the average service life value is in most cases different from the half-life value. Because a gamma distribution is usually defined by a shape and a scale parameter, and cannot be solely defined by its half-life, all of the above-mentioned parameters are provided in Fig. 8 for comparative purposes.

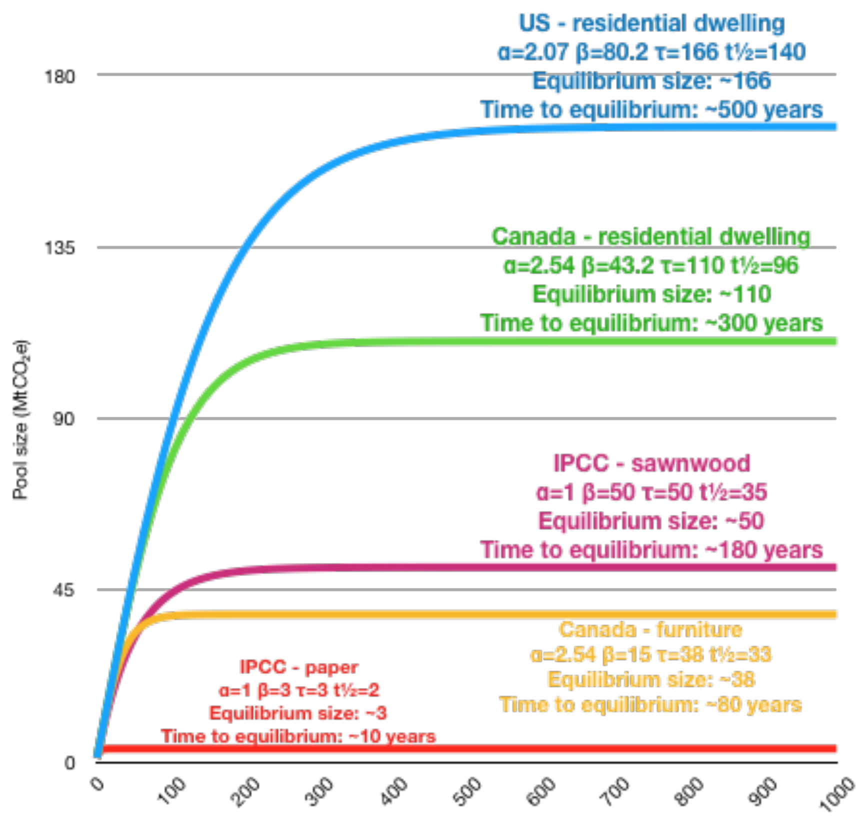

Figure 8. A comparison of equilibrium pool sizes and times to equilibrium among various wood product end uses and commodities. Constant annual input of 1 $MtCO_2e$ to various wood products end uses, assuming gamma distribution retention pattern for residential dwellings and furniture [98–100] and exponential decay retention pattern for sawnwood and paper [47]. The α and β values indicate the shape and scale parameters of the gamma distribution. When α=1, the gamma distribution is equivalent to the first order decay pattern. τ value indicates the average service life. t½ indicates the half-life.

Under these conditions, the wood in residential dwellings in the US and Canada results in equilibrium pool sizes of 166 and 110 $MtCO_2e$, which are three or four times the pool size of furniture. When compared to paper, they are 36 to 54 times larger. Energy uses of woody biomass (e.g., wood pellets) were not modeled because the carbon is instantaneously oxidized and no carbon storage benefit is achieved. The sink periods of construction uses before reaching equilibrium are 500 and 300 years, which are also much longer than furniture and paper applications. Fig. 8 generally indicates that in this time horizon (i.e., 1000 years), the service life value is the dominant contributing factor to the equilibrium pool size and the time to reach equilibrium whilst the decay patterns only contribute marginal difference. Detailed observations were presented in our previous research [99]. Fig. 8 also demonstrates that diverting wood flows from short to long term uses can significantly increase HWPs' ability to act as a carbon sink and mitigate climate change. Additional emission reductions through the substitution of emissions-intensive building materials are reviewed in the following section.

1.4.5.1.1.2 Substitution benefit

Substitution benefits are the emissions reduction benefits achieved by choosing to use a more environmental-friendly material or energy source instead of an emission-intensive material or fuel. The substitution benefit is usually quantified by the displacement factor (DF) proposed by Schlamadinger and Marland [104]. It quantifies the amount of emission reduction achieved per unit of wood use and indicates the efficiency of the substitution effect. The DF was defined as the mass unit of carbon emissions avoided per mass unit of carbon contained in the additional wood used (e.g., tC emissions avoided $(\text{tC in additional wood})^{-1}$) [30] (Eq. 1). The mass unit of carbon in the numerator and denominator cancels and the DF is dimensionless.

$$DF = \frac{CE_{less\ wood\ intensive\ application} - CE_{more\ wood\ intensive\ application}}{CW_{more\ wood\ intensive} - CW_{less\ wood\ intensive}} \qquad (1)$$

where, DF is the displacement factor, CE is the carbon emissions of a less or more wood intensive application during its life cycle, and CW is the amount of carbon contained in the wood products.

Because the building sector is one of the world's major GHG emission contributors accounting for 40% of the global energy use [105–107], published literature investigating the HWP material substitution benefit has been substantially focused on wood products as a building material compared to the functional equivalencies of other materials [28, 30, 108, 109]. The preferred method of calculating the DF of wood replacing concrete and steel as a building material is to use the results of a comparative LCA between functionally equivalent more and less wood intensive buildings. While there have also been attempts to calculate the weighted average DF for wood products based on utilization partitions at the commodity level (i.e., sawnwood and panels) [110, 111] to be used in accordance with the 2013 IPCC tier 2 method [47], Seppälä et al. [112] pointed out that computing the substitution benefit with the displacement factors of individual commodities and their production volumes alone would lead to an overestimation of the climate benefit of forest utilization and should not be used to justify an intensified forest harvest. He and his colleagues proposed to use a new methodology to calculate the threshold displacement factor for all HWPs that is required (RDF) in order for a forest management strategy to beneficial. If the weighted average DF of individual products and end-uses is less than the RDF, an intensified forest harvest may lead to net increase in emissions. Rüter et al. [113] and Hafner and Rüter [114] used the shifts in HWP end-use market shares instead of applying the DFs on the entire HWP production volumes to avoid the overestimation of substitution benefit. Ch. 4 of this thesis also adopted this method.

LCA studies have shown that wooden building products have lower embodied carbon than the other building materials [109, 115]. Embodied carbon describes the material-related proportion of GHG emissions throughout a building's life cycle including material supply, transport, manufacturing, construction, repair and disposal [116]. Therefore, when wood products are used to replace steel, concrete or brick in constructions, a mitigation benefit can be achieved through embodied emission avoidance. Rüter et al. [113] and Werner et al. [109] reviewed comparative LCA studies of wood products used in the building sector compared to their functional equivalencies, and reported the displacement factors of single- and multi-family residential dwellings with the data granularity at the construction element level. The values ranged between 0.7 and 3.3 with wooden windows having the higher values and wood fiber insulations having lower values. The structural components were estimated to be within the range of 0.9 and 2.0. Sathre and O'Conner [30] conducted a meta-analysis and estimated that the displacement factors of wood constructions mostly lay in the range of 1.0 to 3.0. A literature review by Geng et al. [108] observed the same DF range. Leskinen et al. [28] studied the overall synthesis of the topic and provided an updated list of displacement factors with structural components averaging 1.3 and non-structural elements 1.6. The report also identified two important research gaps in this area: 1. a lack of information for product applications other than construction-related, and 2. a lack of geographical representation other than North America and the Nordic countries.

In addition to the embodied emissions, Sartori and Hestnes [117] and several others (e.g., [118–120]) have indicated that the operational energy has a dominant contribution (over 80%) to the GHG emissions of a building's life cycle compared to the embodied energy. Operational emissions include the GHG emissions during building's service phase (e.g., heating, cooling, lighting and appliances) whereas embodied emissions cover the emissions among rest of the phases. These publications suggest priorities to be made on improving heating and cooling system and wall and floor insulation instead of the choice of structural material. Other studies [105, 115, 116, 121, 122] have acknowledged the significance of operational energy, but also indicated that as buildings become more energy efficient and jurisdictional standards become tighter, the relative share of embodied emissions compared to the operational emissions is increasing. Additionally, even though embodied emissions are less significant than operational emissions, they are still large. Choosing a building material with lower embodied carbon provides near-term emission avoidance which is an attractive solution in today's climate crisis and can "buy time" for continued improvement in clean technologies. For this reason, it is common for comparative building LCAs to assume that buildings would meet the same insulation requirement and have the same operational emissions (e.g., [123]). In the comparative building LCA conducted by John et al. [124], the operational performance of the timber building was iteratively designed and simulated to achieve the energy benchmark of reinforced concrete. The results indicated displacement factors ranging between 0.7 and 1.4, which are slightly lower than the above-mentioned values that excluded the operational emissions. Given the uncertainties around the displacement factors, an uncertainty analysis is warranted for the estimation of substitution benefit of timber constructions, which is addressed in Ch. 4.

Other positive wood material substitution examples include furniture such as wooden shelves and office furniture substituting for equivalencies from steel, packaging products such as wooden pallets substituting for plastic pallets, textile products such as wood-based Viscose, Modal and Lyocell substituting for polyester from oil derivates [110, 113, 125, 126]. However, not all forest biomass applications provided positive substitution effect. Some wood material uses can have higher embodied emissions than their equivalencies. For example, several LCAs have indicated that large scale digital media replacing paper products would result in less emissions [127–130]. On the other hand, Bull and Kozak [131] pointed out that the dynamic nature of information and communication technologies (ICT) can result in the life cycle inventory data and LCA results to be outdated quickly. Previous literature also acknowledged the substantial uncertainties related to substitutions other than construction due to lack of research [28]. Both individual LCA and review articles have indicated that geographical locations can cause significant variations in substitution benefits due to the differences in transportation distances, energy mixes, policies and standards, and therefore regional-specific displacement factors are required for accurate accounting of substitution benefits [28, 30, 108, 109, 120, 124, 126, 132]. Because most furniture, textiles, packaging and ICT products are manufactured in developing regions [133], the production volumes of these other end-uses in the researched areas (i.e., North America and Nordic countries) were insignificant compared to construction applications. Consequently, the magnitude of the substitution benefits generated by applications other than buildings is less attractive to the policy community in these regions and as outlined in their climate action plans, primary effort has been focused on construction [60, 67]. Since the target of this study is to quantify BC's GHG emission reduction potentials, the estimation of wood material substitution benefit was also focused on timber construction.

1.4.5.1.1.3 Mass-timber construction technology

Approximately 95% of the single-family houses and 85% of the low-rise multi-family dwellings in North America are built with wood [80–82, 86, 134], which means the potential for increased substitution benefits in these building types will be trivial. On the other hand, large substitution potentials exist in mid- to high-rise dwellings and non-residential buildings [82, 135–138]. Mid-rise wood buildings started to emerge from 2009 when BC changed the building codes to allow wood framed buildings to reach 5 to 6 stories in height [139]. The province is expected to allow 12 stories mass timber constructions in the next iteration of the building code and the federal building code is expected to follow in 2020 [140]. The International Code Council plans to allow wood buildings up to 18 stories in 2021 [141].

Over the past decade, the mass-timber construction technology has advanced substantially and created great opportunities for cross-laminated timber (CLT) and glue-laminated timber (GluLam) manufacturing in Canada. Forty-four tall wood building demonstrations have been built or are planned in the western nations between 2014 and 2020 [142]. BC and Canada are key players in this field but the US and EU are not far behind. Signature buildings include the 6 stories Wood Innovation and Design Centre in Prince George, Canada built in 2014; the 10 stories Trafalgar Place in London, UK built in 2015; the 14 stories Treet in Bergen, Norway built in 2015; and the 18 stories Brock Commons Tallwood House in Vancouver, Canada built in 2017.

The technology is evolving and solutions to structural issues, fire and moisture protection, acoustics and vibrations have been actively addressed [143–146]. However, the major challenge of the widespread adoption of mass-timber constructions may be the cost [147]. A report from the concrete and steel community estimated that the mass timber option currently is 16% to 29% more expensive than reinforced concrete [148]. In contrast, other studies demonstrated that mass-timber is a cost competitive option [149, 150]. Cazemier [151] conducted financial analysis between CLT and concrete buildings and indicated that although mass-timber buildings may have a lower development profit and margin, due to their prefabricated nature, a 35% reduction in construction and time can be achieved, and consequently, it is an overall cost competitive investment option. Cost analysis conducted by McFarlane, Green, Biggar (MGB) Architecture + Design also demonstrates that significant cost reductions are achievable and mass-timber solutions will be more beneficial when carbon pricing is in place [152]. The benchmark costs of 12 and 20 stories mass-timber buildings are estimated at approximately 18 and 30 million dollars or 283~300 dollars per square foot (ft^{-2}). This estimation matches the building budget of Brock Commons Phase 1 of 221~316 dollars ft^{-2} [153–155]. For comparison, the Ponderosa Commons Cedar House concrete building for similar function and size is constructed at a cost about 206~273 dollars ft^2 [155–157]. According to the disclosed budget and funding source, the innovative tall wood buildings are presently subsidized by the government. A survey conducted by Forestry Innovation Investment (FII) [146] indicated that external funding played an important role in construction material decisions. A quantitative assessment of mitigation potentials for BC's timber constructions can advise policy and investment decisions on the value of carbon price. It can also provide quantitative information for future socio-economical analysis on construction-focused mitigation strategies.

1.4.5.1.2 Energy use

When forest biomass is combusted for energy, its carbon content is assumed to be instantaneously oxidized. Therefore, from a carbon accounting perspective, wood-based bioenergy is not considered to have a storage benefit [101]. Depending on the time frame considered, the forest biomass feedstock types utilized, and the carbon intensity[1] of the fossil fuels to be substituted, wood-based bioenergy may provide positive or negative substitution benefit [159–161]. This section reviews mitigation options when wood is used to provide energy.

1.4.5.1.2.1 Substitution benefit

Earlier studies of bioenergy assumed carbon neutrality of the biomass feedstock because the carbon emissions would be sequestered by plant regrowth and they estimated mitigation benefits as high as 80% compared to burning fossil fuels [162–166]. In contrast, Fargione et al. [168] and Searchinger et al. [169] argued that this assumption was flawed. They considered that the use of bioenergy created a carbon debt because the combustion releases carbon immediately but recapturing the emissions may take decades even if no land use change occurred. Laganière et al. [159] calculated the threshold time needed with consideration of land-use emissions for wood-based bioenergy to offset the emissions from fossil fuel alternatives and reach the same carbon volume as its counterfactual (i.e., time to C parity), and the results ranged between 5 and 67 years for bioenergy sourced from forest residues and used for heat generation. The C parity time was at the higher end of the range if it substituted for natural gas, in the middle range for oil and in the lower end for coal. The longer C parity times were calculated if bioenergy was used for power generation.

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[1] Carbon intensity measures the GHG emissions associated with extracting, producing, transporting, and consuming 1 mega joule (MJ) of energy product [158].

Searchinger et al. [169] suggested that the straightforward solution to fix carbon debt is to trace the actual flows of carbon and accounting emissions where and when they occur. For carbon accounting in the forestry sector, combusting wood-based bioenergy is treated as instantaneous oxidation of carbon and therefore carbon neutrality is not assumed [47]. In a mitigation analysis that assesses alternative climate efficient biomass utilization strategies, it is important to quantify the avoided emissions based on the carbon intensities of biofuels and fossil fuels to provide the holistic comparison of different scenarios and to avoid underestimating the mitigation potential of wood-based bioenergy. Rüter et al. [113] and Lippke et al. [24] suggested that energy displacement within a production process should not be accounted as substitution benefit because the embodied emission or carbon intensity LCA will already incorporate the emission reduction effect. For example, burning milling residue within the CLT production process to substitute natural gas will be considered in the embodied emission LCA calculation and this fuel substitution should not be counted again outside the production process. On the other hand, the emission avoided by using wood-based biodiesel to substitute for fossil-based diesel in transportation should be counted as an individual component in the mitigation analysis. Care must be taken when conducting mitigation analyses of HWP product uses to avoid double counting or gaps in the estimation of mitigation benefits.

Published displacement factors of wood-based bioenergy in heat and power generation ranged between 0.4 and 1 [28, 74, 170, 171]. Studies have also shown that when wood-based bioenergy is used to replace coal, the displacement factor is higher; when replacing natural gas, it is lower; and when replacing diesel oil, it is in the middle of this range [74, 110, 159]. A recent review article of displacement factors indicated a lack of knowledge on the substitution benefits of transportation biofuels [28] and this topic is addressed in detail in the following section.

1.4.5.1.2.2 Wood-based "drop-in" biofuel

Human civilization, economic growth and technological advancement are presently heavily dependent on petroleum products. However, petroleum products are fossil carbon from underground and their combustion releases carbon into the atmosphere. The energy and transportation sectors have become the world's major GHG emissions contributors [172]. On the other hand, crude oil reserves are diminishing and mostly located in politically unstable areas [173]. With the concerns of energy supply security, oil import dependencies and climate change, several regions have developed policies to encourage biofuel production [174].

In BC, the transportation sector consumed 80% of the province's total consumption of petroleum fuels [175] and contributed 40% of the province's reported GHG emissions exceeding all the other sectors (Fig. 1). Diesel, heavy fuel oil and aviation fuel consumption represented approximately 50% of BC's transportation energy demand while motor gas contributed the other 50% [175]. Hydro-generated electricity in BC is one of the clean alternatives to petroleum other than biofuel [60]. However, long range transportations such as heavy load freight, marine and aviation are difficult to electrify because the weight of the Lithium-ion battery can be 3 times more than the weight of the rest of the vehicle [176]. For the same reason, the highly oxygenated bioethanol and biodiesel are also not suitable for these applications because they are less energy-dense than their fossil-equivalents and the weight of the fuel is higher than the weight of the payload [173]. Long range transportations therefore require energy dense liquid fuels which provides opportunity for the development of "drop-in" biofuels. A "drop-in" biofuel is a renewable transportation fuel that can be "dropped in" to the existing petroleum infrastructure.

The "drop-in" biofuel can be produced through oleochemical, biochemical and thermochemical means [61]. Oilseeds and animal fats have been used as feedstocks in oleochemical pathways for commercialized "drop-in" biofuel production. However, these feedstocks are expensive and frequently compete with food uses [173]. Woody biomass is considered to be a non-food low-cost potential feedstock which can be converted through biochemical routes, with the use of enzymes, and thermochemical processes, through pyrolysis, gasification or hydrothermal liquefaction (HTL) technologies [174]. The primary forest biomass feedstock sources include the residues from forest management activities such as thinnings, harvest residues and stumps, and secondary sources from industry by-products such as sawdust, wood chips and black liquor [177].

Research and development of wood-based biofuels have achieved breakthroughs over the past 20 years and some pathways have reached demonstration (e.g., Amyris, synthetic biology [178], Steeper Energy, HTL [173]) and commercial scale (e.g., Ensyn, pyrolysis [179, 180]). However, the full commercial deployment of drop-in biofuels still faces major technical and economic challenges. For example, in the biochemical conversion pathways, the intermediate products may have higher financial values than the end fuel [181] and therefore previous commercial attempts have failed [182]. Woody biomass contains high levels of oxygen and impurities that require extensive processing, such as upgrading with hydro-treatment and more frequent turnover of enzymes or catalysts [183].

Thermochemical pathways also encounter challenges of scale. For example, the capital cost of building a gasification plant is high and therefore it needs to be built at a large scale in order to be commercially viable [184]. As forest residues are often widely distributed, an economically viable solution to the supply chain of harvesting, treating, transporting, storing and delivering the desired quantity of forest biomass to the gasification plant does not presently exist [174, 185]. However, other researchers have pointed out that BC has exported 2 Mt year^{-1} of wood pellets, a product that apparently economically competes for forest residue feedstocks [186–188]. An LCA study estimated that the transportation emissions associated with shipping wood pellets to Europe is 295 kgCO_2e (t of pellets)$^{-1}$ [189], which means that the shipping of wood pellets alone contributed almost 0.6 MtCO_2e year^{-1}. Another forest and wood processing industry feedstock competitor is the pulp and paper sector. Approximately 40% of BC's harvested biomass (26.33 Mm^3) was used by pulp mills in 2016 [35]. BC's pulp and paper industry is export-focused with 75% of the pulp being exported with the remaining 25% manufactured into paper in BC, of which 75% is exported [35, 190, 191]. Therefore, in a similar manner to wood pellets, the vast majority (94%) of BC's pulp and paper products were exported. If the "drop-in" biofuels become a more technologically and economically viable biomass utilization option than wood pellets and pulp and paper, the issue of insufficient biomass feedstock supply to the required biofuel plants may be resolved.

The economic performance of biofuels produced via thermochemical pathways ranged from 0.51 to 1.29 dollars L^{-1} (minimum selling price, MSP) [181, 186, 192–195]. For comparison, the average gasoline wholesale price was approximately 0.5 dollars L^{-1} in 2016 [196]. Using the 2016 gasoline wholesale price as a baseline, Nie and Bi [186] estimated that the carbon tax needed to reach approximately 150 dollars tCO_2e^{-1} for the "drop-in" biofuel to break even with petroleum fuels at about 1.0 dollar L^{-1} (MSP) . In 2019, the gasoline wholesale price has increased to 0.93 dollars L^{-1} (Vancouver) and 0.71 dollars L^{-1} (Canada) [196], which may provide economic opportunities for the further development of "drop-in" biofuels in BC and Canada.

HTL and pyrolysis pathways have been actively researched [173, 179, 185, 197, 198] and commercial scale production may be possible [180, 186, 199–202]. Ensyn's pyrolysis facility in Ontario, Canada produced 11 million L year^{-1} in 2014 [201]; the facility in Quebec, Canada was expected to achieve 28 million L year^{-1} and was collaborating with Honeywell to develop a 38 million L year^{-1} biocrude facility [203]; the BTG Empyro pyrolysis project in Hengelo, Netherland achieved 20 million L year^{-1} in 2017 [204], and the Licella-Canfor joint-venture planned to build an 80 million L year^{-1} biocrude HTL production facility in British Columbia, Canada [200, 205].

The yield of "drop-in" biofuels from forest biomass feedstock varied from 0.24 to 0.34 kg biofuel (kg biomass feedstock)$^{-1}$ [185, 193, 197]. Sensitivity analyses indicated that the yield of biofuel, facility locations, electricity mix, by- and co-product utilization have substantial impacts on biofuel's emission performance and price competitiveness against petroleum fuels [186, 206, 207]. For example, Nie and Bi reported that the life cycle GHG emissions (i.e., carbon intensity) of "drop-in" biofuels produced by the HTL process were 10~14 gCO_2e MJ^{-1} using BC's electricity mix and 33~37

$gCO_2e\ MJ^{-1}$ using Alberta's electricity mix [197]. Other studies have reported the emissions of HTL biofuels to be 27 $gCO_2e\ MJ^{-1}$ [193] and 18~20 $gCO_2e\ MJ^{-1}$ [206]. The pyrolysis pathways were reported to have higher emissions than the HTL pathway with the following range of values cited 21~27 $gCO_2e\ MJ^{-1}$ [180], 26~28 $gCO_2e\ MJ^{-1}$ [185], 22~37 $gCO_2e\ MJ^{-1}$ [206], 34 $gCO_2e\ MJ^{-1}$ [193]. For comparison, the carbon intensity of fossil fuels was 84~93 $gCO_2e\ MJ^{-1}$ [185, 193, 206, 208–211]. This research used the published carbon intensity values to estimate the displacement factor range for drop-in biofuels and conduct uncertainty analysis to evaluate their substitution benefits.

1.4.5.2 Trade

The commercialization of "drop-in" biofuel relies on the security of biomass feedstock supply. As the biofuel production facilities scale up, BC may have to redirect the biomass from short-lived low quality export products to biofuel production. Restructuring BC's forest sector for more long-lived applications also depends on both the domestic and international markets. Trade therefore is an important factor in mitigation strategy development. Greenhouse gas emissions are reported to the UNFCCC at the national level and the jurisdictional boundaries usually define the scope of carbon accounting in regards to international activities, in particular trade activities. At the moment, the internationally agreed carbon accounting approach for HWPs is the production approach [47, 48]. The implications, emission consequences and strategies of trade are reviewed and discussed in this section.

1.4.5.2.1 Production approach

The production approach mandates countries to report C emissions and storage from all wood products that are *produced* from the domestic harvest, regardless of where they are consumed [101] (Fig. 9). Consequently, in addition to reporting the C emissions and storage in the domestic grown and consumed HWPs, a jurisdiction is also required to report emissions and storage in domestic grown and exported HWPs. Emissions and storage in the imported HWPs have to be excluded. The harvesting country therefore needs to cover the emissions arising from any form of combustion and decay beyond the national border but is also able to build up an international C stock if the exported wood products are used as materials.

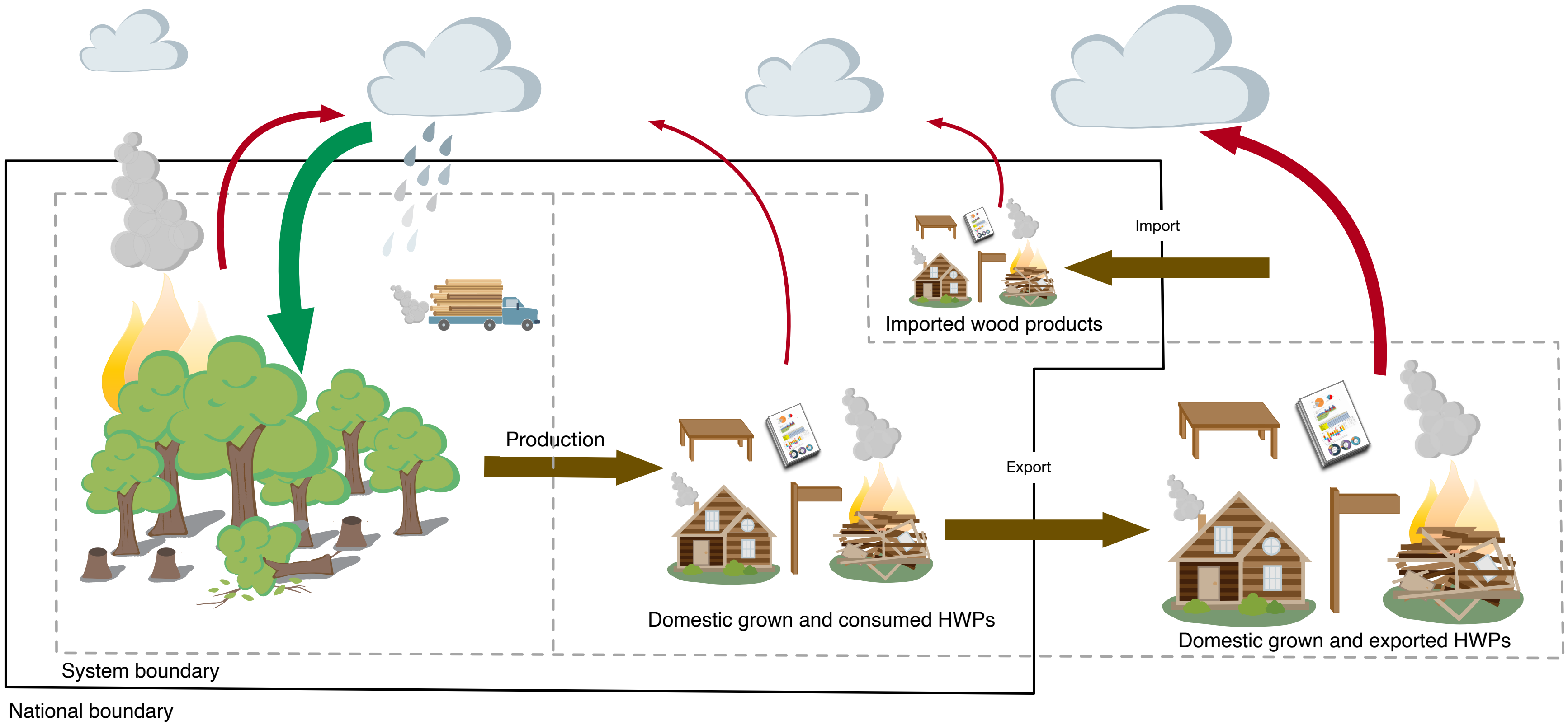


Figure 9. System boundaries and national boundaries of the production approach [101]. The national boundary includes all emissions and storage within the national border. The production approach system boundary includes emissions and storage in the domestic grown wood products (domestic consumed + exported) but excludes those in the imported wood products.

1.4.5.2.2 Implications for carbon storage of British Columbia's harvested wood products

British Columbia's HWP consumption is constrained by the relatively small domestic market size in comparison to the harvest volume [78]. The adoption of the production approach allows BC to report additional carbon storage outside its jurisdictional boundaries, by taking advantage of the foreign market. However, because exported HWPs are consumed beyond the jurisdictional boundaries, BC and Canada's regulations and policies have little control over their end-uses and end-of-life practices. If a large proportion of exports is used for short-lived purposes such as paper and wood pellets, an increase in HWP emissions may occur. In addition, as importing countries are not required to account for C storage nor emissions from imported HWPs, there is little incentive from a carbon accounting perspective for these nations to optimize the service lives of imported wood products.

1.4.5.2.3 Implications for substitution benefits

Discrepancies exist in regard to the system boundaries for different IPCC accounting sectors when reporting to the UNFCCC, which consequently creates difficulties in identifying the mitigation beneficiary from a substitution effort.

The IPCC Guidelines have separated emissions accounting into four sectors: Energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU) and Waste [101]. A production-based approach is used for some products in the IPPU sector and HWPs in the AFOLU sector when reporting to the UNFCCC [47, 48, 101]. However, emissions from the energy sector are accounted for differently using a consumption-based approach (referred to as the sectoral approach in the IPCC Guidelines) in which the energy emissions occurred within the Parties' jurisdictional boundary need to be reported but emissions from exported energy products are not (Fig. 10) [101].

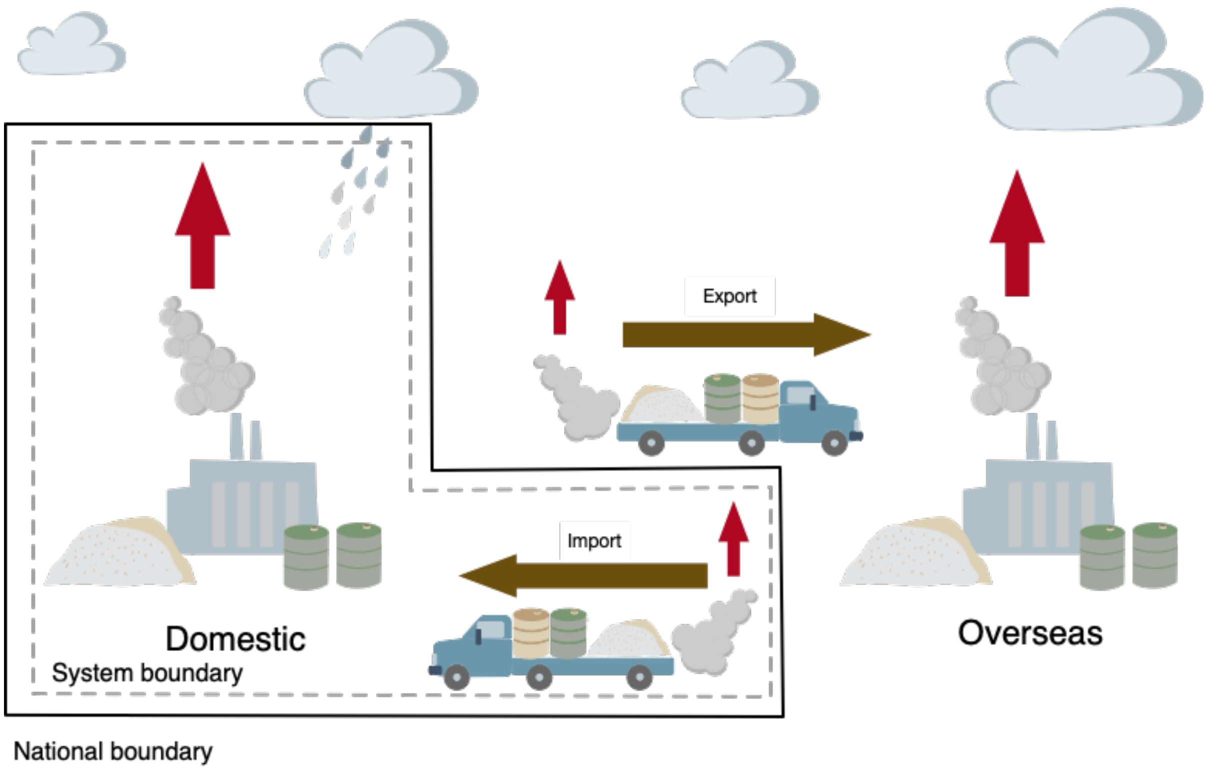


Figure 10. System boundaries and national boundaries of the sectoral approach [101].

Therefore, depending on the origin of the material and the destination of the fuel being displaced, the beneficiaries can vary from an accounting perspective. For example, if wood pellets produced in BC were used to substitute for coal in the electricity generation process in the United Kingdom (UK) (assuming that the coal being substituted is not consumed elsewhere in the UK), then the accounting beneficiary would be UK, because UK's energy sector would achieve an emission reduction from combusting pellets in place of coal. However, the downstream emissions arising from burning these wood pellets in UK and the upstream emissions associated with producing these wood pellets in BC would all be accounted as emissions in BC's AFOLU and IPPU sectors. On the other hand, the use of HWPs for structural purposes rather than pellets for combustion are treated differently. For example, consider CLTs produced in BC, exported to the US and used to substitute for a functionally equivalent amount of steel imported from China. Assuming that this amount of steel was not produced, then China would achieve an emission reduction in its IPPU sector (i.e., a substitution benefit); BC would achieve a foreign storage benefit in the AFOLU sector; the US *may* benefit from reduced energy emissions associated with material transportation (as BC is closer to the US than China) and erecting the structure (due to the prefabricated nature of CLTs and its rapid construction process).

In the two simplified examples presented above, the reduced consumption of coal and the reduced production of steel due to substitution effects have been assumed. In reality, such reduction may not be guaranteed without international cooperation on mitigating climate change. The development of regional forest sector mitigation strategy may also have to face trade-offs between domestic and global substitution benefits. BC as a major HWPs exporter, if its HWPs are used by another jurisdiction to substitute fuels, the substitution benefit will unlikely be recognized on BC's provincial GHG inventory report. On the contrary, manufacturing or burning these HWPs generates emissions that need to be reported by BC. When the substitution benefits of various utilization and trade scenarios are quantified in Ch. 4, these trade-offs will be discussed in detail.

For the purpose of national or provincial inventory reporting, the quantification of substitution benefit is not needed, because the HWP substitution effects, where these occur, will be reflected in the form of emission reductions in the IPPU and energy sectors. However, simply reporting the emission reductions observed in these sectors will not provide sufficient information to trace their cause or to evaluate the effectiveness of the adopted mitigation strategy, and the latter is necessary both from a political and a policy development viewpoint. A rigorous quantitative estimation of the substitution benefits is essential to strategic planning. It then can be used to compare to the emission outcome to help identify issues and enhance the mitigation policy.

1.4.5.3 Cascading uses of postconsumer wood product commodities

Previous sections described possible mitigation options in the use phase of wood product. This section focuses on one of the end-of-life practices. The cascading uses of postconsumer wood commodities are an end-of-life practice that transfers the same woody biomass through a hierarchy of product life cycles [212] (Fig. 11). Postconsumer commodities are a generic term that refers to a collection of commodity wood products that are retired from their current end-use. Examples of these commodities includes lumber, panel and paper products that have reached the end of their service lives in construction, furniture, industrial uses, packaging etc. The cascading uses of resources, not limited to woody biomass, was proposed by Sirkin and Houten in 1994 [213]. Fraanje [214] first discussed the feasibility of a Dutch wood cascading system in 1997. This topic has become an important component of the circular economy [215].

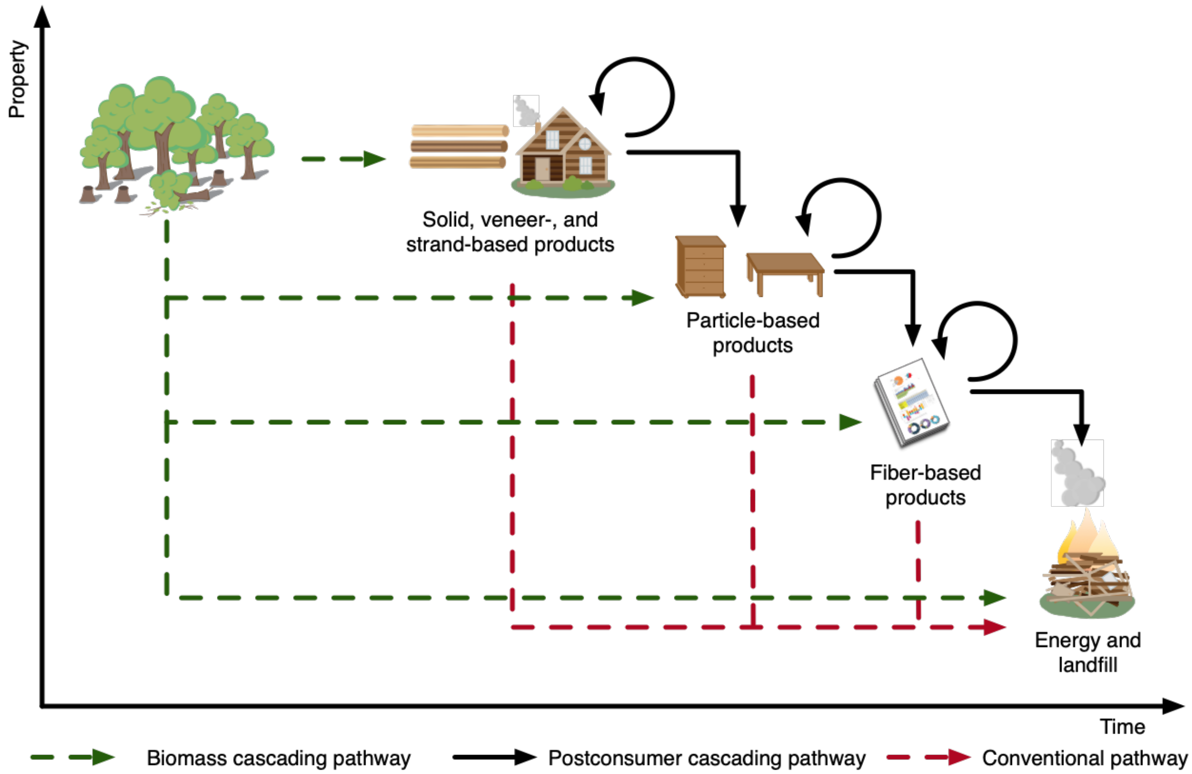


Figure 11. The concept of a cascading use of wood [215–217].

The idea of cascading uses started with resource scarcity [213]. The concept is to achieve highest utilization efficiency by using and reusing the same resource over several life cycles [218]. Although the economics have been the main consideration in the wood processing chain (e.g., paper manufactured from recycled pulp to save raw material cost), it strongly overlaps with the climate mitigation strategy of long-term carbon storage in wood products. The use of postconsumer wood in cascades may provide three potential benefits from a carbon perspective: longer carbon retention times, reduced harvest intensity, and increased substitution benefits [216, 219]. However, establishing an actual cascading system still faces substantial technological, financial and cultural challenges [212, 215, 220].

Interview-based research has indicated that physical quality is one of the major concerns restricting the application of wood cascade system [221]. Werner et al. [222] indicated that chemical contaminants in postconsumer wood products are the key reason of prioritizing energy recovery as the presently favored reuse option in Finland, Germany and Sweden. The size and quality of the postconsumer wood has substantial impact on the yields of cut-off lumber, strands, particles, fibers and pulp which are used make finger joints, OSB, MDF, particleboard and paper. Husgafvel et al. [223] predicted that furniture and packaging would be the most feasible material applications of postconsumer wood, given the current technology of solid composite wood products processing. Jarre et al. [215] reviewed wood cascading literature and found that adhesives, preservatives and paints were identified as obstacles to establishing a cascading economy, but technical solutions remained uninvestigated.

Most recoverable quality wood material is expected to arise from the construction sector (Fig. 11) [224]. However, typically buildings are constructed for their performance rather than being designed for material reuse. The long service life of wooden construction may also prevent designers and developers from adopting the best end-of-life practices. For the recovery of wood in construction demolitions to be feasible, additional effort needs to be placed on the design phase [215] and regulations and building codes also need to be updated [221].

Policy gap analysis has indicated that there is a lack of specific incentives and legislative obligations for the collection and recycling of postconsumer wood products in the construction sector [223]. Germany and Finland have classified waste wood into different categories based on treatment type and amount of chemicals [212]. A case study in south-east Germany indicated that 25% of the wood in the demolished building stock is suitable for reuse and 21% can be redirected to lower cascade applications [225], but the lack of policy inducement and market demand are still bottlenecks in the realization of large scale material reuse of postconsumer wood products because collection, sorting, treatment, remanufacture and commercialization pose greater financial risk than simply selling them for incineration [226]. The overhead cost of processing facilities is also comparatively high as most combustion facilities are already in place [222, 227]. The current sorting solution for postconsumer wood products is visual-based, which is labor-intensive [216]. A more accurate alternative would be via expensive chemical analysis which requires the use of near infrared spectrometry, X-ray and fluorescence analysis [212, 216, 221]. If the collection, remanufacturing and marketing facilities are sparsely distributed and processed by different companies, the logistics would constitute the largest share of cost [228]. Upgrading and expanding existing facilities such as sawmills to have remanufacturing capability may be a potentially cost-effective solution and this approach is used in Ch. 5 of this thesis to conduct mitigation analysis for the cascading uses of postconsumer wood products.

Many previous studies have focused on comparing climate performances between particleboard manufactured from recycled wood and direct incineration of waste wood (e.g., [219, 229]). Their results indicated that the climate benefit may be insignificant when the energy required to produce the particleboard and the biomass losses during each cascading step are considered. The mitigation potential beyond particleboard production and incineration is not well quantified. BC presently has not established a well-regulated wood cascading system. A quantification of the upper-bound and practical emission reduction potentials of the cascading uses of BC's postconsumer wood products would be a logical first step to help determine whether it is worthwhile to conduct further socio-economical and policy-related investigations.

1.4.5.4 Leakage

Any changes in consumption arising from a regional mitigation strategy may be accompanied by some degree of carbon leakage [230]. Carbon leakage describes a mitigation issue that arises when emission-intensive activities migrate from one jurisdiction to another that has weaker restrictions [231]. Regional climate policies such as the EU's energy efficiency and shares of renewable energy targets may cause leakage [231] (e.g., wood pellets exported from BC to the EU), part of which is due to the discrepancies in accounting approaches used, as discussed in Section 1.4.5.2.3 (Implications for substitution benefit). The IPCC [231] summarized the scenario-based studies and indicated that *energy-related* leakage rates are relatively small, mostly below 20%; Boehringer et al. [232] reported that the leakage rates are approximately 12% and Calvin et al. [233] estimated them to be less than 10%. On the other hand, *land-use-related* leakage can be substantial but it is difficult to quantify and only few studies have tried [231]. Fragmented and uneven regional climate policies have been highlighted as the major cause of carbon leakage with Rose and Sohngen [234] estimating that global leakage may be as high as 100 $GtCO_2$ due to delayed carbon taxes in some regions between 2010 and 2050. Concerns of leakage have also been expressed regarding the EU's emission trading system (ETS), the largest cap and trade system in the world, as the credit generated by unilateral emission reduction would allow new emissions to arise within the trading regime [231]. However, Barker et al. [235, 236] argued that the ETS would improve the EU's overall competitiveness and the leakage would be small due to technological spillover which means a greater actual emission reduction than expected (i.e., negative leakage). Robust approaches to quantify and avoid leakage are yet to be developed.

The concept of carbon leakage partially overlaps with the effects of energy rebound, which describes the potential issue of increased energy consumption due to increased energy efficiency that leads to cheaper energy and higher income [231]. Similar to the issue of carbon leakage, the rebound effects are also difficult to quantify. This research did not consider a detailed quantification of carbon leakage or energy rebound but acknowledges the potential impacts of them and as a first step, aims to avoid relocating emissions arising from domestic market demand to the other regions. In the design of mitigation scenarios in this study, domestic demand for various wood product end-uses (long-lived, short-lived, or energy uses) was required to be fulfilled first before the remaining biomass can be used to explore utilization and trade options for climate mitigation (see Mitigation scenarios section in Ch. 3 for more details).

1.4.6 *Harvested Wood Products Carbon Dynamics Model*

In the 1960s, the climate science community expressed an increasing concern over the warming effect of increased levels of carbon dioxide in the atmosphere [237]. The development of carbon accounting models for the forestry sector started in the 1980s [238–241] when the Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to assess climate change based on the latest science (Fig. 12). In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted by the United Nations (UN) and the convention recognized forests' capability to sequester and store carbon. However, the early forest C models normally do not include carbon dynamics in HWPs [242]. In 1995, the first IPCC Guidelines were published, but harvested wood products were not mentioned [243]. This first version was soon being replaced with the 1996 IPCC Revised Guidelines and 1996 to 2006 marks a decade of continuous effort on developing neutral accounting guidelines for HWPs [244]. The 1996 Revised Guidelines suggested an instantaneous oxidation as the default approach based on the perception that HWP stocks are not changing [245] because it was assumed that the sum of the inputs was equal to losses. Meanwhile, an approach for estimating the net CO_2 emissions from forest harvesting and wood products was forwarded to the IPCC Plenary in 1996 and was included as part of the 1996 Guidelines [245]. The UNFCCC therefore requested its Subsidiary Body for Scientific and Technological Advice (SBSTA) to further its technical work on approaches. In 2001, the IPCC notified the subsidiary body its intention to include HWPs in the Guidelines [244]. Consequently, the 2006 IPCC Guidelines included HWPs in Chapter 12 [101]. The chapter introduced the tiered methods, accounting approaches, the use of a first order decay model and default half-life parameters for different HWP commodities (i.e., sawnwood, panels and paper). Although the IPCC has updated the progressive scientific understanding of HWP carbon storage, decisions are usually compromised by the political nature of the negotiation process [242] and HWP C reporting was not immediately added in as a requirement for National Inventory Reports (NIR). During the Conference of the Parties (COP 17) in 2011, HWPs were finally accepted as accounted carbon pools [48, 246] and all Annex I countries were subsequently required to report changes in HWP C stocks while Annex II countries can report on a voluntary basis.

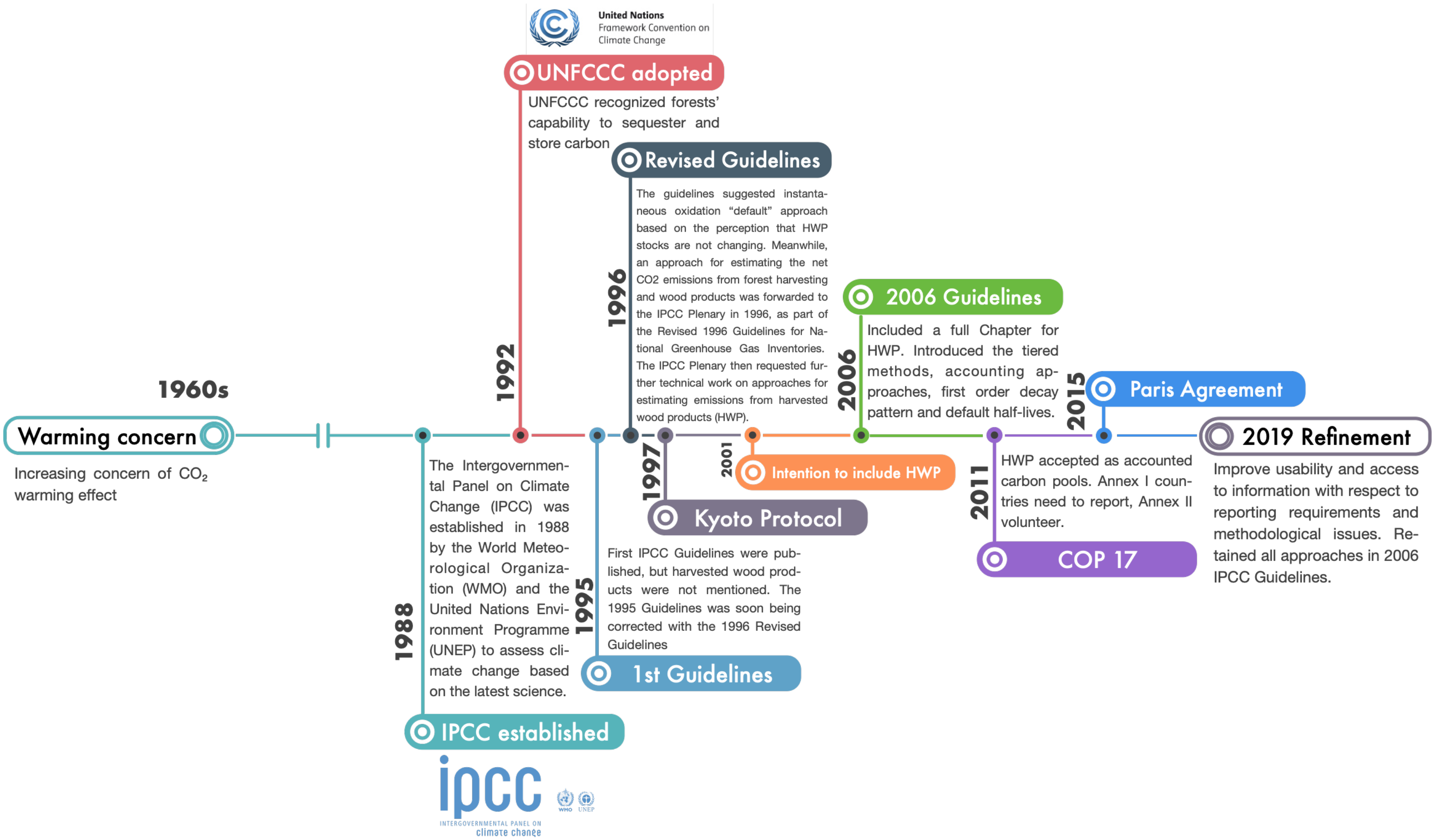


Figure 12. A brief timeline of international discussion on harvested wood products carbon accounting [237–246].

Numerous of HWP carbon accounting models have been developed over the years to conduct emission reporting, stock estimation, substitution benefit estimation and mitigation scenario analysis. Jasinevičius et al. [242] reviewed 9 HWP C models and categorized them into 3 groups based on their modeling principles: bookkeeping, material flow and LCA. Bookkeeping models use the IPCC first order decay default values and directly apply to production volumes at the wood commodities level (i.e., sawnwood, panel and paper) [247]. Material flow models track carbon dynamics at each production, consumption, trade and utilization stage after harvest until their end of life [222]. LCA models are usually used to measure the substitution benefit [248]. Brunet-Navarro et al. [249] evaluated 41 HWP C models by two sets of indicators on the comprehensiveness of structure and the ease of use. He and his colleagues identified common errors in existing models due to over-simplification of the hierarchical structure of biomass flow in the wood products processing chain.

In the earlier ages of HWP C modeling design and development, the main focus was to accurately report the C emissions and storage to the public, government or international organizations (e.g., UNFCCC), and this type of model can be termed IPCC Guideline-based reporting models (or "*reporting models*"). Such a model typically uses historical sawnwood, panel and paper production data (e.g., from the FAOSTAT database [133]) to estimate the carbon stocks and emissions from HWPs (Fig. 13). A number of existing and previous versions of HWP C models fall within this category (e.g., CARBINE [239, 250], CO2FIX version 1.2 [251], WOODCARB II [22, 100], Pilli et al. [21], C-HWP [252–255]).

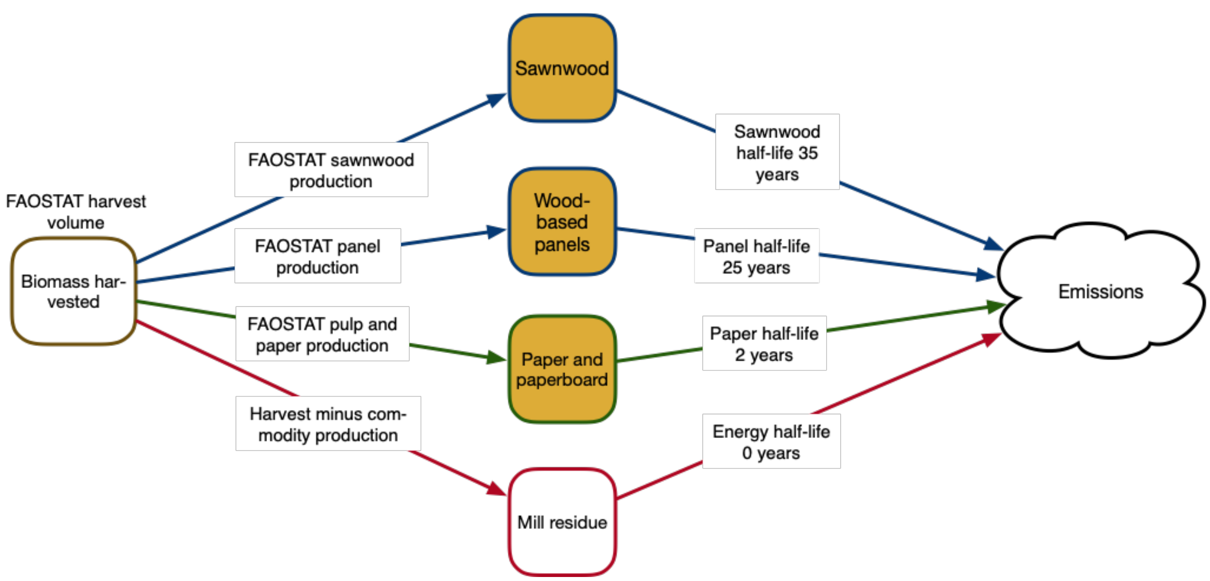


Figure 13. Conceptual framework for IPCC Guideline-based reporting models.

These *reporting models* are designed to have a simple structure but are sufficient for their purposes as long as the country-specific production data and mass-weighted-average half-lives for sawnwood, panel and paper are accurate. Since the HWP production has already occurred, the requisite data are mostly available. These models estimate the current year's HWP C pool sizes by multiplying the remnant rates (determined by the half-lives) with the previous year's pool sizes and this year's production C inflows (Eqns. 2, 3 using the sawnwood carbon pool as an example). They estimate the emissions by summing this year's production C inflows with previous year's pool sizes minus the current year's estimated pool sizes (Eq. 4 using emissions from the sawnwood pool as an example).

$$C_{sawnwood}(i) = C_{sawnwood}(i-1) \times e^{-\lambda} + Inflow_{sawnwood}(i) \times [\frac{1-e^{-\lambda}}{\lambda}] \qquad (2)$$

$$\lambda = \frac{ln(2)}{half-life_{sawnwood}} \qquad (3)$$

$$E_{sawnwood}(i) = inflow_{sawnwood}(i) + C_{sawnwood}(i-1) - C_{sawnwood}(i) \qquad (4)$$

where, $C_{sawnwood}(i)$ is the currect year's sawnwood C pool size; $C_{sawnwwod}(i-1)$ is previous year's sawnwood C pool size; e is Euler's constant; $E_{sawnwood}(i)$ is the current year's emissions from the sawnwood C pool.

The *reporting models* have also been used to estimate future HWP C storage and emissions but the analyses are limited to a lower resolution and a general understanding of the changes in HWP sink magnitudes with respect to uncertainties over future harvest volumes (i.e., the initial input to the model). For example, Pilli et al. [21] conducted an analysis with changing harvest rates (±20%) that resulted in EU's HWP sink to range between -9 and -43.2 $MtCO_2e$ $year^{-1}$. He and his colleagues recognized that the changes in HWP end uses and market conditions are important factors that cause fluctuations of HWP carbon pools, however, because the model was designed at the resolution of HWP commodity level (sawnwood, panels and paper), the study has to rely on correlations between harvest and commodity production to conduct estimations. Rüter [252] used the same approach and estimated the emissions from HWPs based on harvest projections of different countries in the EU. However, these two model examples were not designed to specify detailed mitigation suggestions other than indicate the amount of pool size changes in the future under broad scenarios. The robustness of the *reporting models* is limited when they are used to evaluate a scenario containing more specific mitigation requirements [249], such as the impact of an increased market share of timber construction on wood pellet production. This is because the *reporting models* often are not equipped with a sufficiently sophisticated biomass flow structure from high to low quality utilizations. For example, increasing lumber production will lead to an increased production of chips, sawdust and shavings which are the raw materials for downstream manufacturing processes such as panels, paper and bioenergy.

As jurisdictions legislate their climate mitigation targets, the purpose of carbon accounting has also evolved beyond simply reporting the magnitude of historical and current carbon sinks. The HWP C models are required to answer "what-if" questions for mitigation strategy development, which means that they must have the ability to quantify the GHG emission reductions of a given mitigation effort in a specific area such as renewable transportation fuels, built environment and waste management. Some existing models were initially designed for reporting purposes but have evolved over several iterations to include more complex flow structures (e.g., CO2FIX ver. 1.2 to 3.1 [251, 256, 257]; FORCARB ver. 1 and 2 [258–260], FORCARB-ON ver. 1 and 2 [90, 261–263]; models that belong to the Carbon Budget Modeling Framework for Harvested Wood Products (CBMF-HWP) family: NFCMARS-HWP [42, 46, 264] and BC-HWPv1 [265]). Models within this category are capable of conducting complex mitigation analyses and are termed scenario-based mitigation analytical models (or "*mitigation models*"). Other examples of *mitigation models* include EFISCEN [266] and CAPSIS [267, 268]. A scenario-based mitigation analysis usually involves comparing numerous biomass harvest, trade, consumption and utilization options to a business-as-usual scenario. The results from the model simulation are expected to advise the policy community on future implementable strategy options. Unlike *reporting models* where production data are retrieved from databases, the production, consumption and trade allocations in mitigation analyses sometimes need to be determined by the model according to the scenario configuration. Therefore, some specific modeling components are necessary and the common characteristics of the above-mentioned *mitigation models* include [242, 249]:

- the simulation of carbon allocation in the wood products production process and value chain;
- the capability to handle temporal and spatially explicit production and trade data;
- the inclusion of a variety of wood product commodities or end-uses;
- the capability to model more complex and realistic carbon retention patterns (e.g., Gamma distribution) rather than the first order decay pattern;
- the inclusion of a module to estimate substitution benefits;
- the inclusion of a module to simulate end-of-life practices such as recycling and landfilling.

In Canada, HWP C dynamics models have been actively developed using the CBMF-HWP modeling framework. The CBMF-HWP modeling framework is a software system developed by the Canadian Forest Service [46]. Another example of modeling software is the Carbon Accounting Tool (CAT) developed by Fortin et al. at UMR Silva [269]. In theory, a HWP C dynamics model can be implemented using any modeling software. Many HWP C models are spreadsheet-based models where the carbon flow structure representing the HWP supply chain compartments are predefined (e.g., WOODCARB II, CO2FIX and C-HWP), which lack the flexibility and ease to redesign the flow structure to better represent different scenario requirements and extension of additional pools and modules.

The HWP C models in the CBMF-HWP family have been used for Canada and BC's inventory reporting and mitigation analyses (NFCMARS-HWP and BC-HWPv1). Upon reviewing the studies using these models, some potential improvements to the model were identified. The HWP mitigation strategy examined by Smyth et al. [264] shifted 6.2% of the harvested biomass away from pulp and paper production to increase proportions of sawnwood production by 4.2%, panel production by 1.7% and other solid wood uses by 0.3%. Xu et al. [42] outlined a similar HWP mitigation scenario by shifting 1.6% (2017-2020) and 4% (2021-2050) of the harvested biomass from pulp and paper manufacturing to panel production. However, the raw materials for pulp manufacture are pulp logs, milling residues and recycled pulp. Pulp logs are normally considered to be unsuitable for producing sawnwood. Recycled pulp and milling residues such as wood chips, sawdust and shavings also cannot be used to produce structural panels such as plywood and oriented strand board (OSB). To address these shortcomings, the NFCMARS-HWP model requires stronger constraints in the biomass utilization structure to ensure that biomass only flows from high to low quality production options. Another possible improvement within NFCMARS-HWP would be to re-allocate carbon from commodity pools to end-use pools. This will allow a more realistic and accurate estimation of carbon retention at the end-use level using more sophisticated decay patterns and latest data on service lives [98, 99, 270]. The BC-HWPv1 model designed by Dymond [265] included the carbon allocation at the end-use level and BC-specific half-life values and conversion factors, which allowed more accurate pool size and emission estimations. However, the veracity of the model structure can be further increased. The ability to identify the source of emissions can avoid the overlooked side effects of a mitigation strategy. For example, the bioenergy pool in the BC-HWPv1 model should be further divided into process biomass combustion (e.g., black liquor, hog fuel and onsite energy recovery of chip, sawdust and shavings) and bioenergy feedstocks (e.g., biofuels and wood pellets). Chemical pulp production is associated with substantial emissions from spent pulp liquor combustion which have not been separately identified by the current model structure as they are combined with other bioenergy feedstocks. The existing model is therefore unable to quantify the mitigation benefits of reallocating wood fiber used for pulp production to be used by a nascent "drop-in" biofuels sector. The division of important bioenergy types will also allow the inclusion of submodules that accurately estimate the substitution benefit at a granularity that can distinguish whether an increased consumption of bioenergy is associated with fossil fuel displacement external to the production process [24]. The HWP mitigation scenarios in Smyth et al. [264], Xu et al. [42] and Dymond [265] all focused on manipulating the biomass input on the supply side, but the HWPs market is demand-driven. Scenarios derived from the demand side would help the policy community identify specific market-based climate intervention strategies. Market demand scenario development usually requires the help of an economic model, such as GLOBIOM or GFPM, to determine the production, consumption and trade allocations [70]. In the absence of such economic models, a demand-satisfaction add-on could be developed for CBMF-HWP to allow demand-driven model runs. These improvements will be implemented in Ch. 2.

1.4.7 Knowledge gaps

BC has released the CleanBC plan as its strategic plan to reduce the province's GHG emissions [60]. In particular, the plan recognized HWPs' ability to contribute to emission reductions in the building, transportation and waste sectors. However, it did not quantify the maximum and minimum emission reductions that HWPs could contribute. Assessing the mitigation potentials of timber constructions, wood-based biofuels and cascading uses of wood can inform policy and investment decisions and provide a quantitative basis for future analyses of the socio-economic implications of any mitigation strategy. It has been recognized that long-term carbon storage in timber constructions reduces HWP emissions and provides more time for the forest to regenerate and for climate-friendly technologies to be developed. Substituting wood for concrete and steel as construction materials also reduces emissions from the energy and industrial sectors. Yet, following several decades of declining timber supply in BC, it has not been assessed whether there is enough biomass to meet the demand of long-term applications, or if the domestic and global markets are sufficient and accessible to make this long-term storage strategy viable. The impact of the increasing wood pellets export to the EU due to its renewable energy policy on BC's emission profile has not been assessed in detail; nor has whether producing wood-based "drop-in" biofuels is a better value-adding alternative than exporting wood pellets. In addition, the substitution benefit that is provided by replacing fossil-based transportation fuels with "drop-in" biofuels, when the technology becomes available, has yet to be fully evaluated. Substitution benefits were not, and should not, be included in the national or provincial inventory reports, but their quantification is important from both political and policy development viewpoints because it evaluates the effectiveness and identifies important issues within the mitigation policy. Uncertainties around the substitution benefit of HWPs due to a lack of research have been acknowledged, but uncertainty analysis using BC-specific LCA data has not previously been conducted. This thesis seeks to fill these knowledge gaps in order to better inform policies designed to maximize the benefit associated with using HWP to reduce BC's GHG emissions.

1.5 Thesis structure

Chapter 2 A harvested wood products carbon dynamics model for climate change mitigation analysis

Objective: to design and implement a state-of-the-art carbon dynamics model, named MitigAna, for BC's mitigation analyses.

Chapter 3 Inward- vs. outward-focused bioeconomy strategy for British Columbia's forest products industry: a carbon storage and emission perspective

Objective: to quantify and identify the mitigation potentials and the emission consequences of various inward- vs outward-focused utilization scenarios for BC's HWPs from a direct carbon storage and emission perspective, without considering substitution effects.

Chapter 4 Substitution benefits of British Columbia's forest products for greenhouse gas mitigation

Objective: to quantify and evaluate the substitution benefits of a wood construction- or a wood-based "drop-in" biofuel-focused bioeconomy.

Chapter 5 Forest sector mitigation consequences of cascading uses of British Columbia's wood products

Objective: to determine the potential importance of cascading postconsumer HWPs within BC's forest sector climate change mitigation strategy and policy development through modeling and quantification of the fate of carbon in wood cascades.

Chapter 6 A vision for the BC forest sector that combines mass-timber construction and biofuel production to contribute to domestic greenhouse gas emission reduction targets

Objective: to examine the potential climate benefits of an inward-focused, construction-dominated and biofuel-subordinated bioeconomy in BC.

Chapter 7 Concluding chapter

Objective: to summarize the overall quantitative findings, conclude the hypothesis and research objectives, describe the research limitations and outline future work.

2 A HARVESTED WOOD PRODUCTS CARBON DYNAMICS MODEL FOR CLIMATE CHANGE MITIGATION ANALYSIS

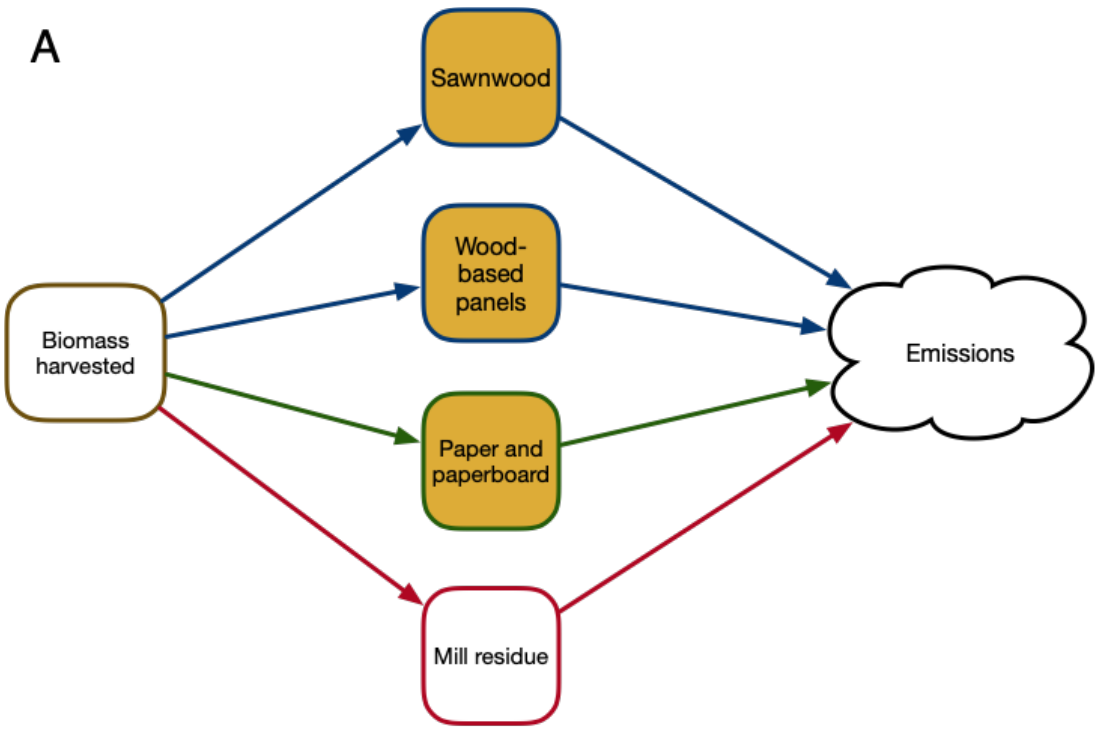
2.1 INTRODUCTION

Modeling the production, consumption, recycling and disposal of harvested wood products (HWPs) by society is complex and therefore a model is needed for HWPs carbon estimation. A model generally makes assumptions and focuses on some processes and stages while simplifying other less important ones. As described in Ch. 1, HWP models in general have two purposes:

1. to estimate and report the HWP carbon storage and emissions to the public, government or international organizations (e.g., WOODCARB II [22, 100]);
2. to compare numerous future HWP greenhouse gas (GHG) mitigation options (e.g., EFISCEN [266]).

For reporting historical and recent HWP carbon storages and emissions, a simple structural model may be sufficient because the required production and consumption data are usually available. This type of model can calculate the pool size by summing the carbon in various HWP commodities (e.g., sawnwood, panel, pulp and paper and biofuel) and the emission amount by adding up the carbon in HWP commodities that are burnt or sent to landfills.

For an analysis of various future mitigation options, a more comprehensive model is required [249]. One of the challenges of using a simplified model structure for mitigation analysis is the lack of necessary constraints. While it is sensible that a reporting model does not use constraints in order to keep it lean and simple to use, it can result in erroneous mitigation strategies. For example, the structural applications of wood are considered to have greater climate benefit than pulp and paper end-uses. A simple structure model such as the one shown in Fig. 14A may suggest a biomass input shift away from pulp and paper industry directly to sawmills and composite mills [264]. However, biomass of different quality has different uses. The raw materials for pulp manufacture are pulp logs, milling residues and recycled pulp. Pulp logs are normally considered not suitable for producing structural lumber. Recycled pulp and milling residues such as wood chips, sawdust and shavings also cannot be used to produce structural panels such as plywood and oriented strand board (OSB). To explore such mitigation options properly, a model with flow hierarchies that constrain biomass flowing from high to low value utilization is needed (e.g., Fig. 14B).



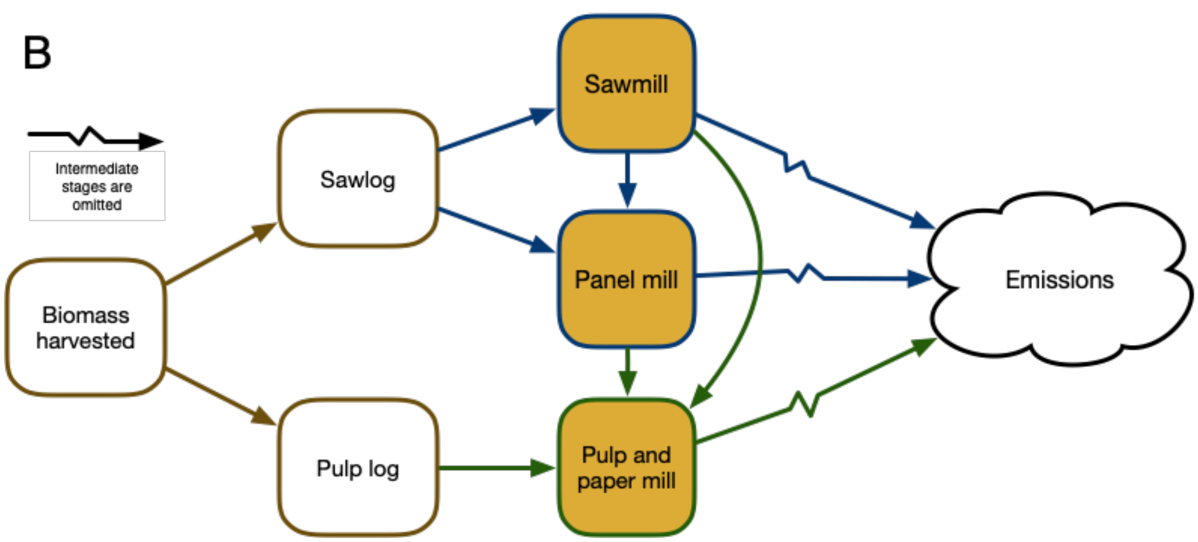


Figure 14. Examples of HWP models with simple structure. A: an IPCC Tier 1 model. B: a model with simple flow hierarchies.

Another challenge of using a simple structural model for mitigation analyses is that the "side-effects" of a new strategy may be overlooked. For example, in a bioeconomy strategy assessing increasing chemical pulp exports to another jurisdiction, a consequential side-effect is the additional emissions caused by black liquor combustion for energy and chemical recovery. This effect may not be captured in such granularity by the models shown in Fig. 14A as these types of emissions may be considered as bioenergy or waste combustion that is inevitable during the production process. The chemical pulp industry may also claim energy self-sufficiency by burning some of its raw materials (i.e., chips, sawdust and shavings) and these by-products (i.e., black liquor) on site for power and heat. However, electricity is predominantly produced by hydropower in jurisdictions such as BC where substituting wood for hydropower provides little to negative climate benefits and these raw biomass inputs and by-products may have an alternative substitution opportunity with greater GHG mitigation potential, for example, producing transportation biofuel to substitute fossil fuel. In jurisdictions where electricity is predominantly produced from fossil fuels, different climate benefits accrue. These detailed alternatives should be captured by a mitigation analysis.

This study sought to learn from published models (e.g., [46, 70, 90, 100, 265, 266, 271–273]) and designed a state-of-the-art carbon dynamics model, named MitigAna, for BC's mitigation analyses. This model will contribute new concepts, practices and principles for this research topic that can also apply to other jurisdictions. The goal of this chapter is to describe the structure, parameters and usage of the MitigAna model.

2.2 MITIGANA MODEL

The MitigAna model was developed by tracing the flow of wood products that are harvested, produced, exported, and consumed by BC with compromises due to data constraints and necessary modeling simplifications. This section will first take a high-level view of the MitigAna model and then demonstrate carbon flows during the commodity manufacturing, trade and end-use application stages.

2.2.1 OVERVIEW

The MitigAna is a harvested wood products carbon dynamics model that simulates the fate of wood carbon for scenario-based mitigation analysis. A review of HWP C models and their relationship to the modelling framework is presented in Ch. 1. The MitigAna model was implemented using the Carbon Budget Modeling Framework for Harvested Wood Products (CBMF-HWP), a modeling software developed by Canadian Forest Service (CFS) [46]. A conceptual view of the fate of carbon in HWP is shown in Fig. 15.

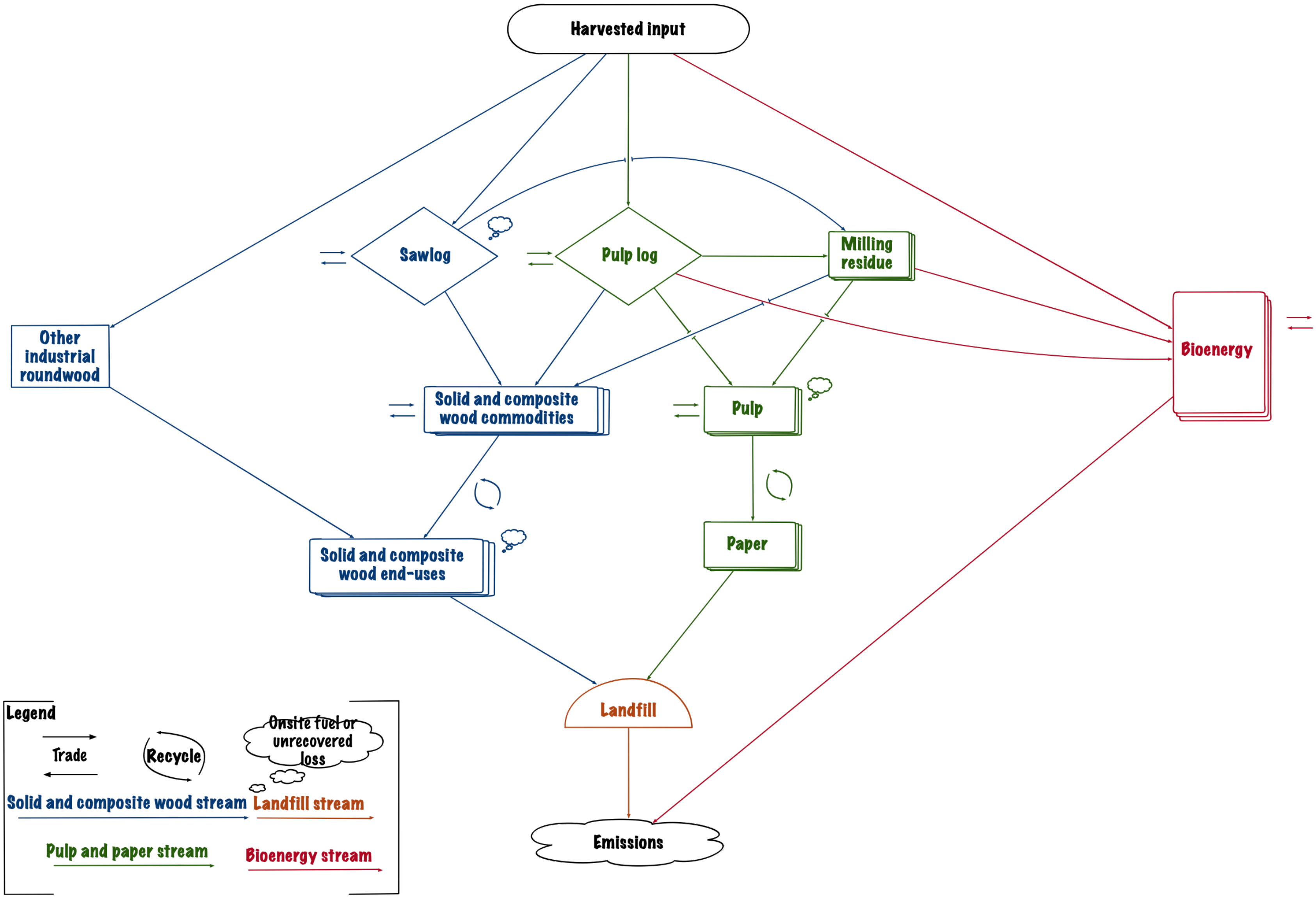


Figure 15. Conceptual HWP carbon flow diagram.

The conceptual flow model started with harvested wood being taken out of the forest and undergoing manufacture and use by society and ended with carbon emission to the atmosphere or non-decomposable carbon storage in a landfill. The MitigAna model used BC's wood products manufacturing flows as the basic structure and to set allocation parameters but it also accommodated BC's trading partners with jurisdictional-specific flow structure and parametric values if details were available from the literature. For example, the US and Japan have different carbon retention parameters for the end-use pools [100, 274] and China has significantly different wood products end-use practices compared to the other major BC wood importers [92].

Each stage presented in Fig. 15 comprises a more complex structure and is divided into more detailed components that are presented below.

2.2.2 Solid and composite wood commodities

A partial view of the carbon flow focusing on the solid and composite wood commodity stream is shown in Fig. 16.

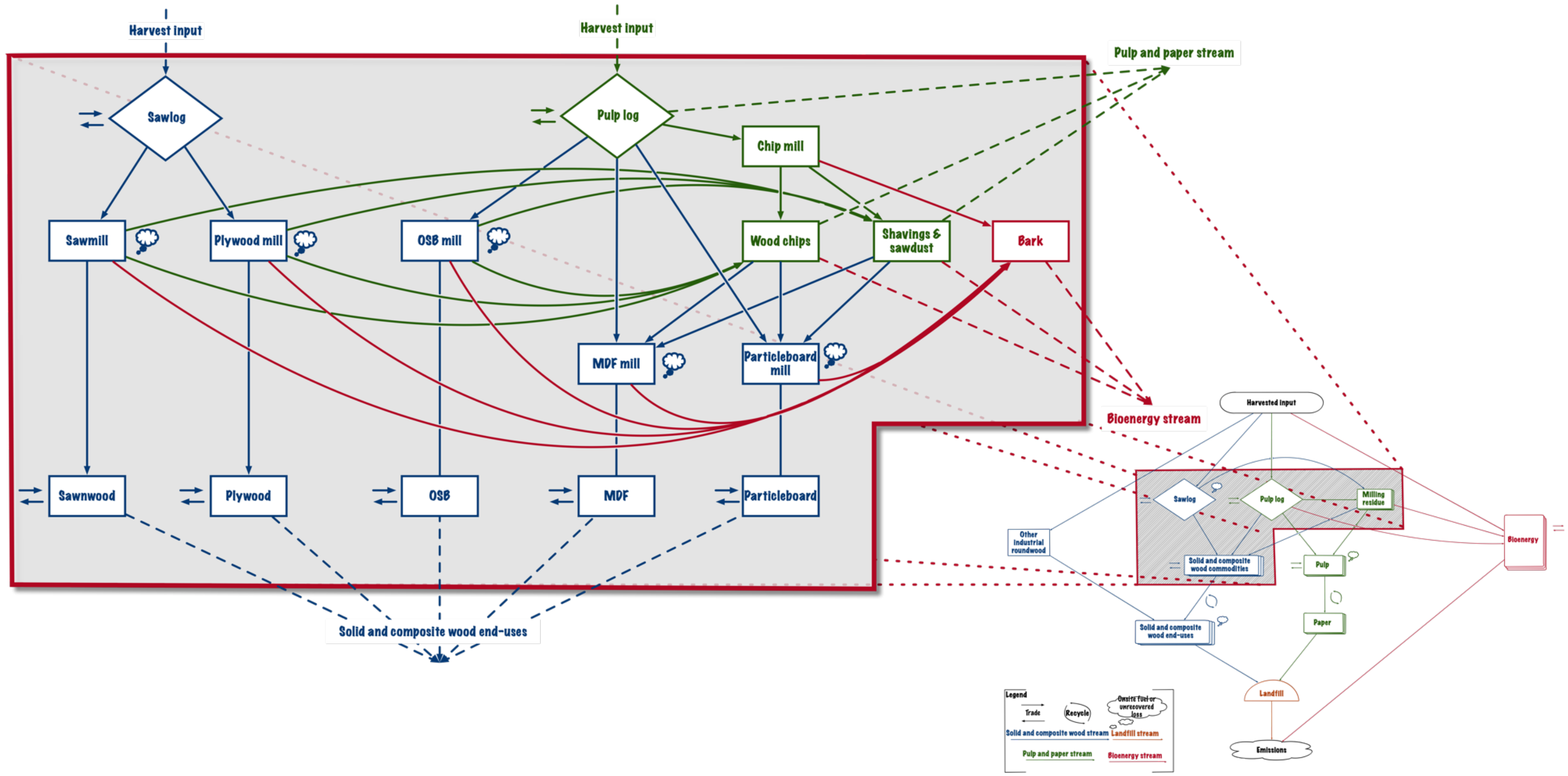


Figure 16. Detailed carbon flow of the solid and composite wood products commodities stream.

In MitigAna, the following five solid and composite wood products commodities were recognized:

1. sawnwood;
2. plywood;
3. oriented strand board (OSB);
4. medium density fiberboard (MDF);
5. particleboard.

The taxonomy of harvested wood products published by Cohen and Ellis [275] was generally followed with reference to FAO's forest products definitions [276]. However, the taxonomy was compromised by the low resolution of some reported production and consumption data with some of the product categories having to be combined. For example, sawnwood included both solid and glued lumber products and engineered lumber composites. In future, these aggregated commodity categories in the MitigAna model may be downscaled which would provide greater accuracy, provided that the data eventually become available.

Utilization hierarchies

Utilization hierarchies have been developed to match industry practice and to improve the rationality of the MitigAna model. The flow schematic in Fig. 16 indicates the biomass utilization constraints. In the flow diagrams of the MitigAna model (Figs. 15, 16 above and Figs. 17, 21, 22 in the later sections), the hierarchy generally follows the rule that upper left is higher than lower right with some exceptions introduced for aesthetic reasons. HWP in a higher position may be utilized the same way as the lower position but not vice versa.

Unlike some previous models [46, 265], the MitigAna model separates sawlogs and pulp logs into two distinct streams to explicitly indicate the utilization barrier between them (Figs. 15, 16) which constrains the amount of sawnwood and plywood that can be produced from the harvested roundwood because pulp logs are usually smaller in diameter and have lower fiber quality. They are technologically difficult to use to produce sawnwood and plywood. On the other hand, sawlogs may be used the same way as the pulp logs, although it is normally not economically beneficial to do so. Milling residues and by-products are also explicitly represented in the model to enable more controls and constraints to be applied to the downstream products. These aspects will be further discussed later.

Further separating panel types into structural and non-structural categories recognizes the distinct raw material requirements for each product type. Structural panels generally are produced directly from logs. Plywood involves peeling the logs into veneers before drying, forming and pressing into panels. OSB requires directly stranding the log into particular length strands (e.g., 4~6" long) which is a size requirement that chips, shavings and sawdust normally cannot achieve. In contrast, non-structural panels are often produced from wood chips and other by-products of primary wood processing.

For mitigation analyses, these types of constraints are essential otherwise the model may shift lower grade biomass to produce higher grade products for long-lived uses and overestimate the mitigation benefits. The constraints also explicitly demonstrate the competition among various utilizations of woody biomass.

2.2.3 Solid and composite wood end-uses

Fig. 17 illustrates the carbon flow in the solid and composite wood products end-use categories.

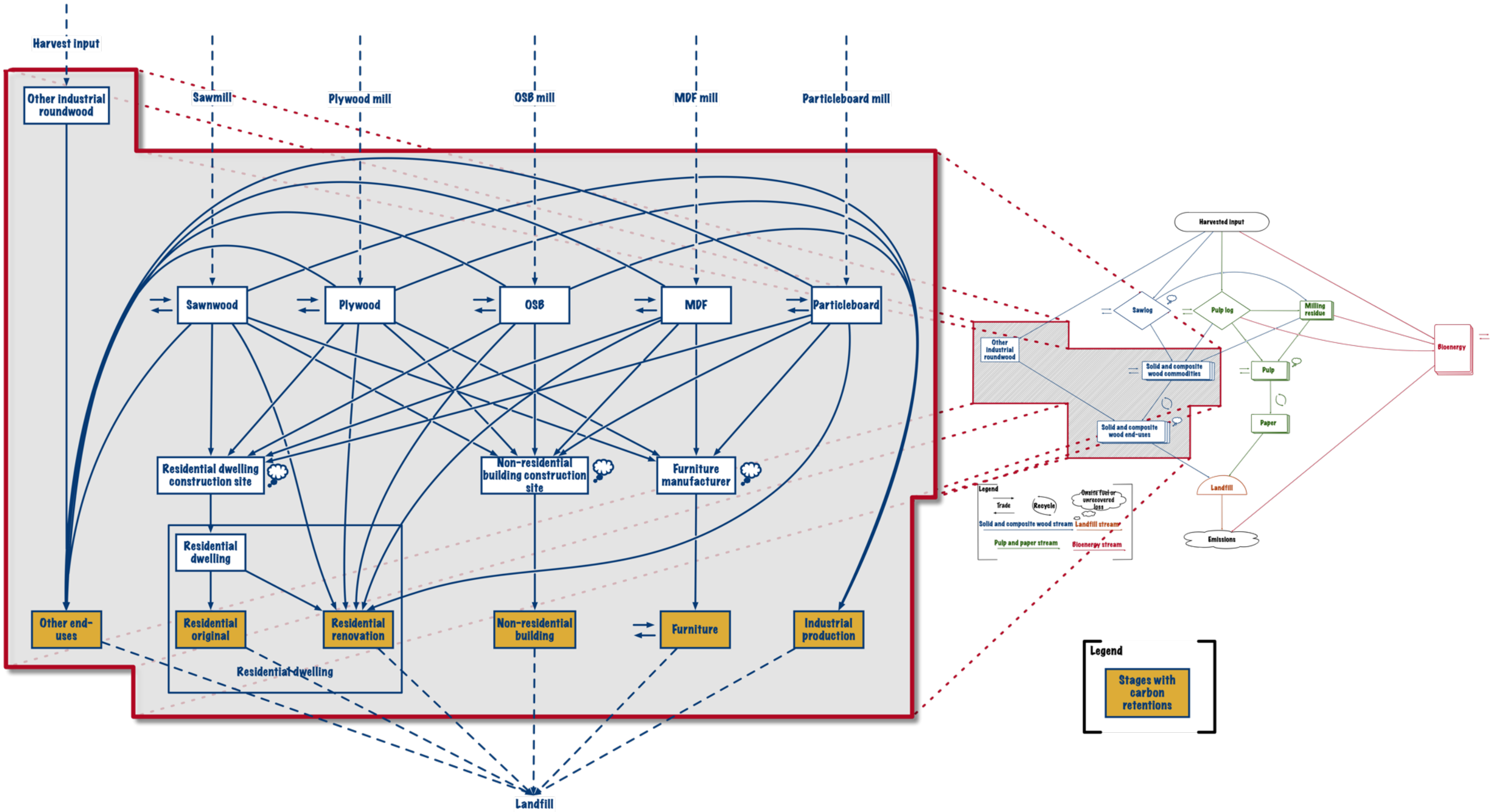


Figure 17. Detailed carbon flow of the solid and composite wood products end-uses.

Six HWP end-use categories were recognized in MitigAna: residential dwelling, residential renovation, non-residential building, furniture, industrial production, and all the other end-uses which were not captured by the previous categories. This categorization aligned with the end-use consumption data that were available [81, 82, 84–91]. Tbl. 2 provides examples of each end-use category.

Table 2. Examples of end-uses. (CLT: cross laminated timber; GluLam: glue laminated timber).

End-use categories	Examples
Residential dwelling	Studs, joists, wall panels, staircase, cabinets
Residential renovation	Cabinets, doors, window frames, counter tops, floors
Non-residential building	CLT beams, GluLam beams, studs, I-beams
Furniture	Tables, chairs, shelves, nightstands, bed frames
Industrial production	Pallets, concrete forming, crates, barrels
Other end-uses	Electricity poles, fences, crossties

Sawnwood and plywood were widely used in almost all applications. OSB was normally not used for furniture applications. MDF and particleboard were rarely used in industrial productions.

2.2.3.1 Residential renovation

The MitigAna model subdivided the HWP carbon in residential dwellings into two separate categories: residential original and residential renovation (Fig. 17). Residential original referred to wood products that were in the dwelling since it was constructed and remained in place until the dwelling was demolished. Residential renovation referred to wood products that were subject to repair and remodeling over a dwelling's service life. The material that was replaced during a renovation event may be the "founding material" that was in service when the dwelling was completed. It may also be the "renovation material" that was added in during a previous renovation activity. Residential original and residential renovation together represented the carbon pool in residential dwellings.

Residential renovation is one of the major uses of wood products in the recent decade. Nearly half of the annual consumption of solid and composite wood products in Canada is for residential renovation [85, 91]. In the US, the largest importer of BC wood, renovation accounts for about a quarter of their solid and composite wood products consumption [84]. Therefore it is important to accurately account for the use of HWPs in renovation activities.

Among the wood components of a newly built residential dwelling, some proportion may be subject to repair and remodeling later in the dwelling's service life and some proportion may stay until the dwelling is demolished. For example, the kitchen and bathroom may require renovation every 30 years or so after the dwelling's completion. These types of renovation usually involve changes to the wall panels, cabinets, counter tops and flooring (also non-wood components such as drywalls, tiles and plumbing), but it is less common to make changes in the structural components, such as the studs. Another type of renovation is remodeling such as altering a basement for additional living spaces or extending the garage. Remodeling may involve structural alternations and extensions.

Previous carbon models accounted for the wood products used for residential renovation as a separate pool with a specific carbon retention function parallel to the other end-uses, if the model distinguishes different end-uses (e.g., Fig. 18). This approach implies that all the wood in the newly built dwellings would last until demolition.

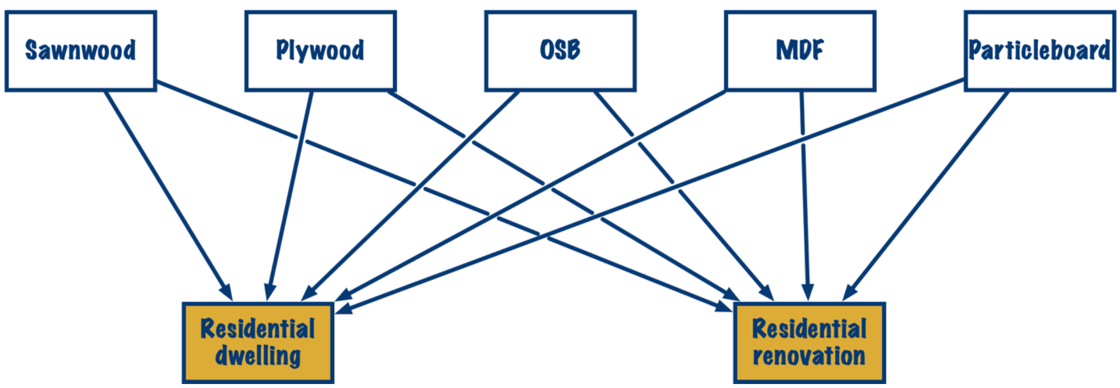


Figure 18. Previous models account renovation as a separate pool parallel to the other end-uses

This approach is likely to cause double counting for at least one renovation cycle as shown in the conceptual framework presented in Figure 19 and discussed below. For simplicity, the following illustration (Fig. 19) assumed that the service life of a residential dwelling is 80 years; its renovation cycle is 30 years and the service life of the renovation material is also 30 years. Wood used to build the dwelling is termed the "founding material" and wood used to repair and remodel the dwelling is termed the "renovation material". In this simplified illustration, when the dwelling has been in service for 30 years, it requires a renovation. If the approach shown in Fig. 18 is applied, in this renovation event, the renovation material is allocated to the "renovation pool". However, because the dwelling has not reached its end of life, the founding material is not retired from the "housing pool". Therefore, new is wood introduced to the carbon pool by the renovation event but no wood exits from the pool. This causes an overestimation of the carbon stock for one renovation cycle. When the dwelling has been in service for 60 years (i.e., the second renovation cycle), new renovation material is introduced to the renovation pool to replace the old renovation material, and the dwelling continues its service until demolition at 80 years.

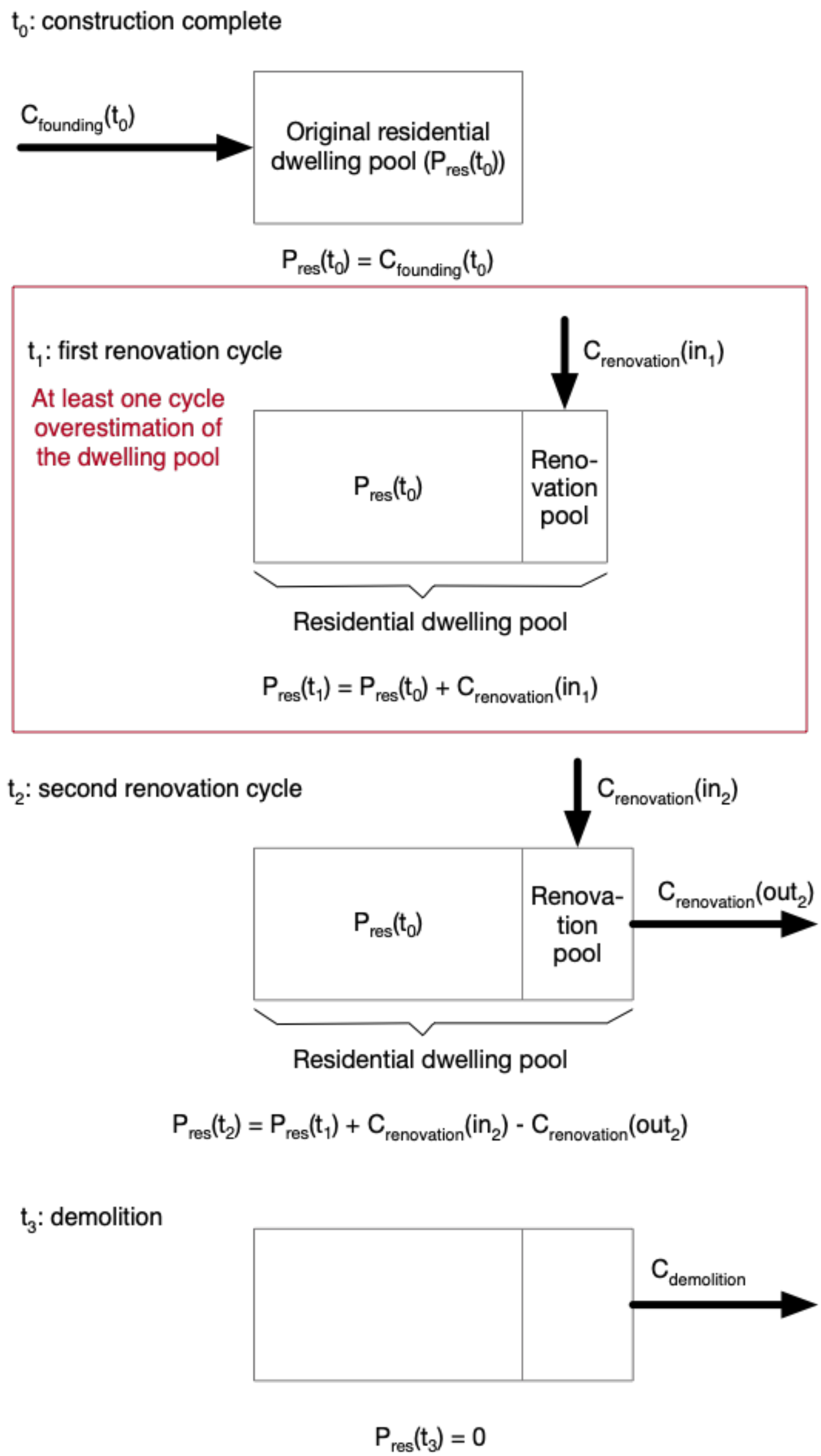


Figure 19. Simplified illustration of how previous model handled renovation. $C_{renovation}$(in) denotes the new renovation input to the pool; $C_{renovation}$(out) denotes old renovation material being replaced.

In a real-world renovation process, at the first renovation cycle, the renovation material may replace an arbitrary proportion of the founding material in the residential dwelling pool as shown in Figure 20. The total carbon content of the renovation material may be higher or lower than the replaced founding material depending on whether the materials have the same specifications. For example, if the founding material is solid wood and the renovation material is a wood composite of the same dimension, because the composites are generally denser, the renovation material may contain more carbon. In this process, the replaced founding material exits the housing pool and the new renovation material enters. When the dwelling reaches the second renovation cycle, the new renovation material may replace an arbitrary proportion of the old renovation material and another arbitrary proportion the founding material.

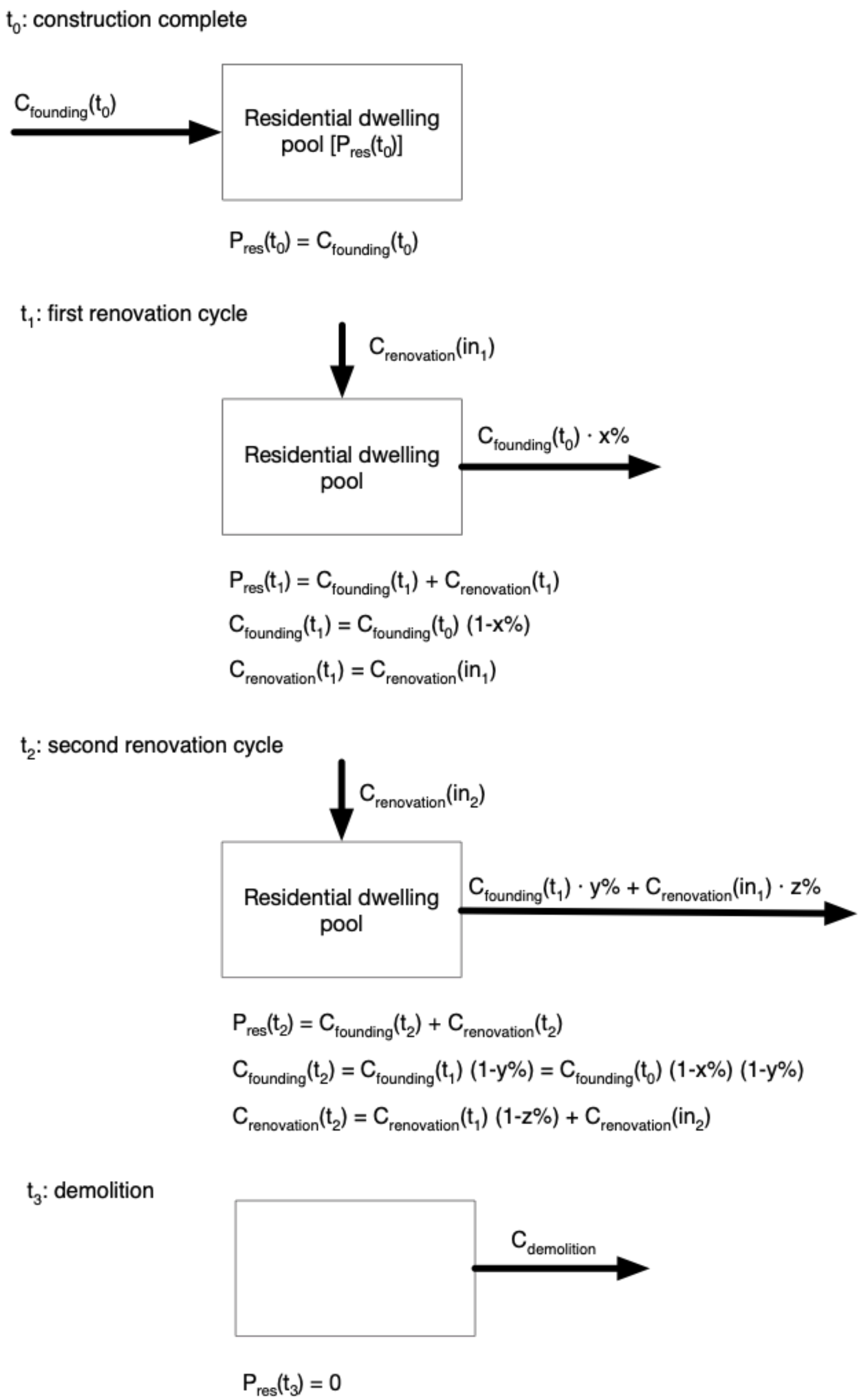


Figure 20. Simplified real world renovation process. $C_{renovation}(in)$ denotes the new renovation input to the pool; $C_{founding}(t)$ denotes carbon stocks of founding material; $C_{renovation}(t)$ denotes the carbon stocks of renovation material in the residential dwelling pool, as opposed to founding material; x%, y% and z% denotes arbitrary percentages.

From a modeling perspective, whether the carbon content of the new renovation material is higher or lower, is less important, because at the macro level, the model will implicitly capture this information as long as two parameters can be estimated. The two parameters are:

1. the average partition of the dwelling pool that is subject to renovation (i.e., the partition parameter responsible for separating "residential original" and "residential renovation" from "residential dwelling" in Fig. 17);

2. the carbon retention pattern of the renovation material. Parameter 1 is essentially an estimated average value that serves as a macro-level representation of the arbitrary proportions (x%, y% and z% in Fig. 20).

Consequently, the MitigAna model introduced this new concept to account the carbon in HWPs used for residential renovation (Fig. 17). A proportion of the founding material at completion was allocated to one pool that was permanent until demolition (i.e., residential original); the rest of the founding material was allocated to another pool that was subject to renovation (i.e., residential renovation). Although this new partition also introduces additional uncertainties, this approach provides a more conservative estimation of the dwelling carbon stock and is closer to the real-world carbon dynamics than previous models (e.g., [46, 90, 100, 265, 266, 271–273]).

2.2.3.2 Carbon retentions for solid and composite wood end-uses

Each solid and composite wood end-use was expected to serve for a period of time termed service life. Each HWP pool would therefore retain all or some of the wood carbon until the end of its life.

The Intergovernmental Panel on Climate Change (IPCC) recommended the use of the first order decay function to estimate the carbon retentions in various situations for the Agriculture, Forestry and Other Land Use (AFOLU) sector (e.g., dead organic matter, harvested wood products, and solid waste disposal) [101]. However, it has been established that solid and composite wood end-uses generally have an expected service life and the peak retirement rate happens near the expected service life instead of at the beginning [98, 99]. This carbon retention pattern is best to be described by the Gamma distribution with a shape parameter, "α", and a scale parameter, "β". The "α" and "β" values for residential dwellings in Canada were estimated to be 2.54 and 43.2 [99]. While housing start, completion and demolition data are relatively easy to acquire, information on the other end-use applications is usually not readily available. It has been noted that the estimated "α" values of the residential dwellings in the US, Canada and Norway do not vary greatly (2.07, 2.54 and 1.80, respectively) [99]. It was therefore conjectured that the carbon retention patterns of solid and composite wood end-uses may be described by Gamma distributions with similar shape parameters. When the "α" value is held constant, the one-parameter Gamma distribution is a subset of the natural exponential family, which is a common simplification practice of the distributions in the exponential family. Therefore, as a first approximation, the "α" values of all other end-uses were assumed to be 2.54. These values can be recalibrated when updated information becomes available. The mean, "μ", of the Gamma distribution (or in our case, the mean service life of an end-use), equals to "α" multiplied by "β". For simplicity and using this property, the mean service life was assumed to be equal to the expected service life. The "β" values were then calculated using μ divided by α (Tbl. 3).

Table 3. Gamma parameters for various end-uses.

End-uses	expected service life (ESL)	μ	α	β	Reference for ESL
Residential original	110	110	2.54	43.2	[99]
Residential renovation	30	30	2.54	11.8	[85, 265]
Non-residential building	75	75	2.54	29.5	[265]
Furniture	38	38	2.54	15	[100, 265]
Industrial production	3	3	2.54	1.18	[92]
Other end-uses	25	25	2.54	9.84	[101]
US residential original	166	166	2.07	80.2	[99]
Japanese residential original	56	56	2.54	22	[274]

2.2.4 Pulp and Paper

Fig. 21 describes the carbon flow in the pulp and paper stream.

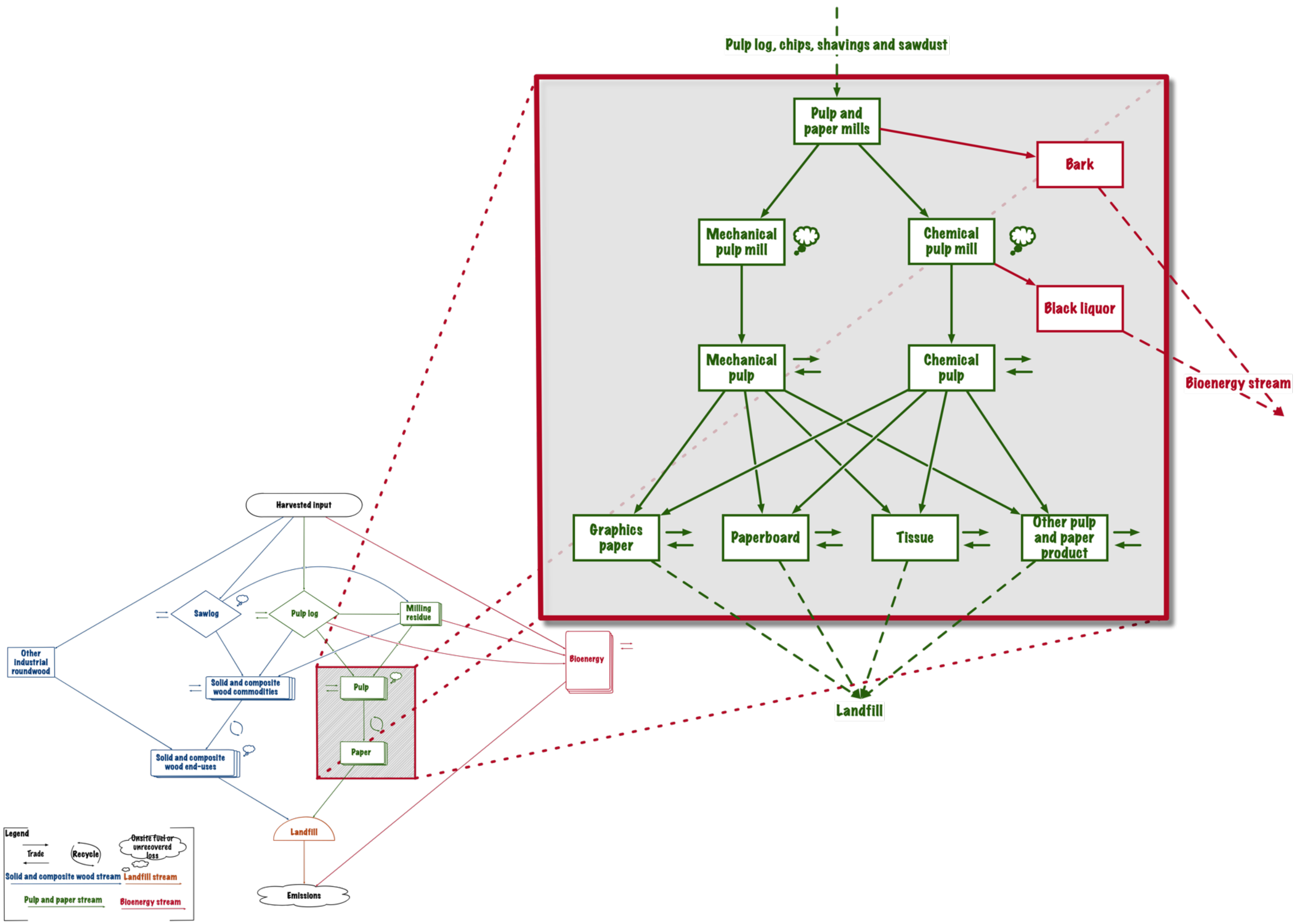


Figure 21. Detailed carbon flow of the pulp and paper stream.

There were three input sources for pulp production in the MitigAna model: pulp log, chips, as well as sawdust and shavings. Approximately 75% of the pulp output was exported and about 25% was used domestically for paper manufacturing. In addition, 75% of the paper manufactured in BC was exported and 25% was consumed in the domestic market [35, 190, 191]. Kraft chemical pulp dominated BC's pulp supply. However, chemical pulp production has a lower yield than mechanical pulp with about half of the carbon in the input fiber ending up as by-products or combusted as energy. One of the major by-products was black liquor. With the same pulp output, the biogenic climate impact can vary two-fold depending on the type of pulp manufactured. Therefore, unlike most previous models, the MitigAna model distinguished the carbon flows in chemical and mechanical pulp production.

2.2.4.1 Carbon retention for paper products

Paper products generally have a shorter service life than solid and composite wood end-uses. Previous models have used a half-life of 2 years and a first order decay pattern for paper products [21, 92, 100, 101, 265]. When applying the Gamma distribution to short-lived uses, the "α" value tends to be near "1", which is close to the first order decay [98]. Consequently, for short lived uses, the first order decay function was used, and for paper products, the half-life was assumed to be 2 years in the MitigAna model.

2.2.5 Bioenergy

Fig. 22 demonstrates a partial carbon flow of the MitigAna model focusing on wood-based bioenergy products. Bioenergy was assumed to be instantaneously oxidized.

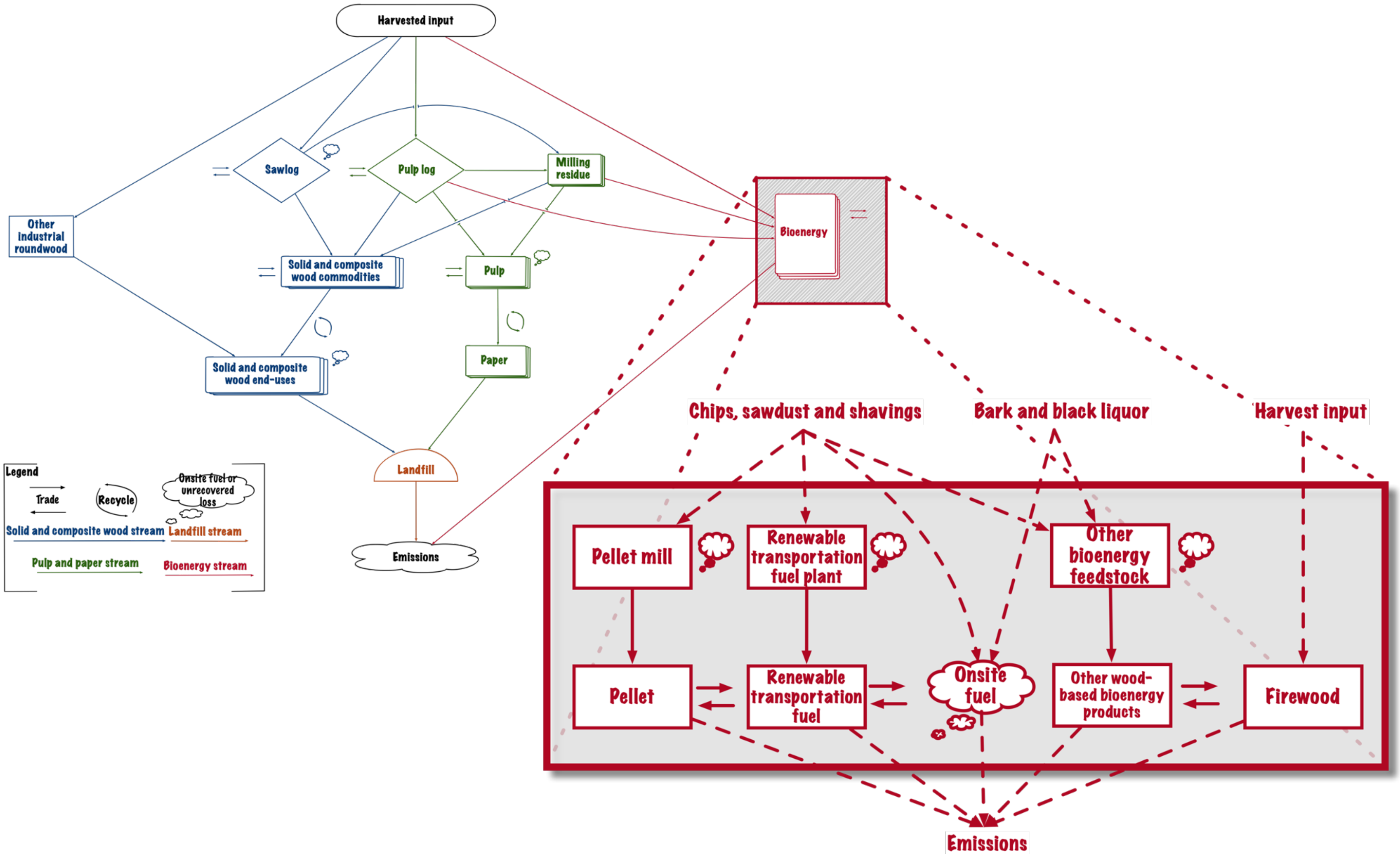


Figure 22. Detailed carbon flow of the bioenergy stream.

The major bioenergy feedstock inputs were milling residues (i.e., chips, sawdust, shavings and bark), by-products (i.e., black liquor) and raw harvest (i.e., firewood). Currently, most of these inputs were used to produce wood pellets in BC. However, recent studies have shown that the renewable transportation fuel may have a promising future [60, 173, 177, 179]. This research therefore investigated the mitigation benefit of this option and consequently the MitigAna model separated this pool from the other bioenergy products. A significant amount of milling residues and almost the entire output of black liquor combustion were used to generate electricity, heat and steam onsite for the mills. Onsite fuels were represented by "cloud" shapes in Fig. 22 and all previous figures in order to avoid an excessive number of arrows further complicating the flow diagrams. While these combustion practices may be economically beneficial for the mills, it is uncertain whether they are climatically efficient. This issue will be discussed in detail in later sections.

2.2.6 *TRADE*

Under the current internationally agreed "production approach" accounting rule, BC is responsible for reporting emissions arising from all HWPs as long as the biomass was originally harvested in BC [47, 48]. The major wood trading partners of BC modeled in MitigAna were the United States (US), China (CN), Japan (JP) and the European Union (EU). The other minor partners were combined as "other (OT)". In total, there were six jurisdictions (Fig. 23).

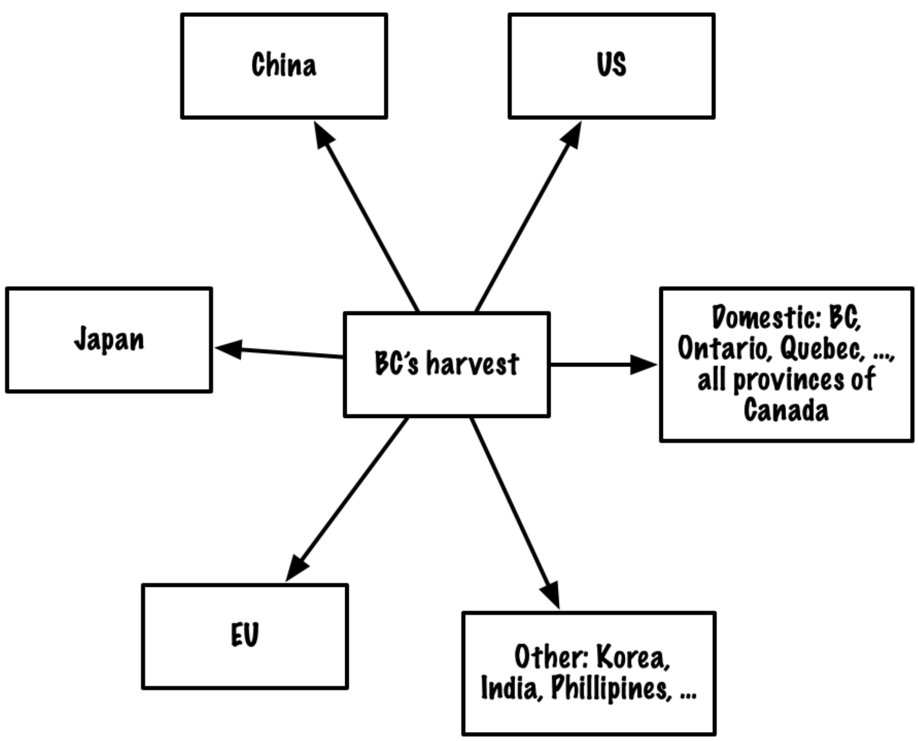


Figure 23. Jurisdictions in the MitigAna model.

Exports and imports are represented by "⇄" in Figs. 15-17, 21, 22. The MitigAna model was capable of handling either a production approach or a stock change approach[2]. The production approach is more difficult to implement than the stock change approach. The production approach accounts for the exports but not the imports and it therefore needs to track the life cycles of all exported HWPs. Therefore, each jurisdiction has its own carbon flow diagram that is similar to Figs. 15-17, 21, 22.

In reality, one jurisdiction potentially can export BC wood to another jurisdiction. From a modeling perspective, this activity is challenging to track and implement because to our knowledge, there are no data publicly available to distinguish multi-layer trading activities. Consequently, the MitigAna only incorporated one layer of trading activity.

The stock change approach accounts for imports but not exports. Hence, only the domestic carbon flow diagram is needed. With the domestic import data available, it is much easier to implement and the uncertainty level associated with trade is much lower. This research modeled the fate of carbon using the production approach to align with the current international accounting framework [47, 48].

2.2.7 CHINA

The solid and composite wood products stream in China is significantly different from those of Canada, US and Japan. The MitigAna model adopted a jurisdiction-specific flow for the Chinese market based on the published model generated from field visits to China in 2015 by Manley and Evison [92]. Such a flow diagram is shown in Fig. 24.

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[2] For the accounting approaches, see Pingoud et al. [277] and IPCC [101]

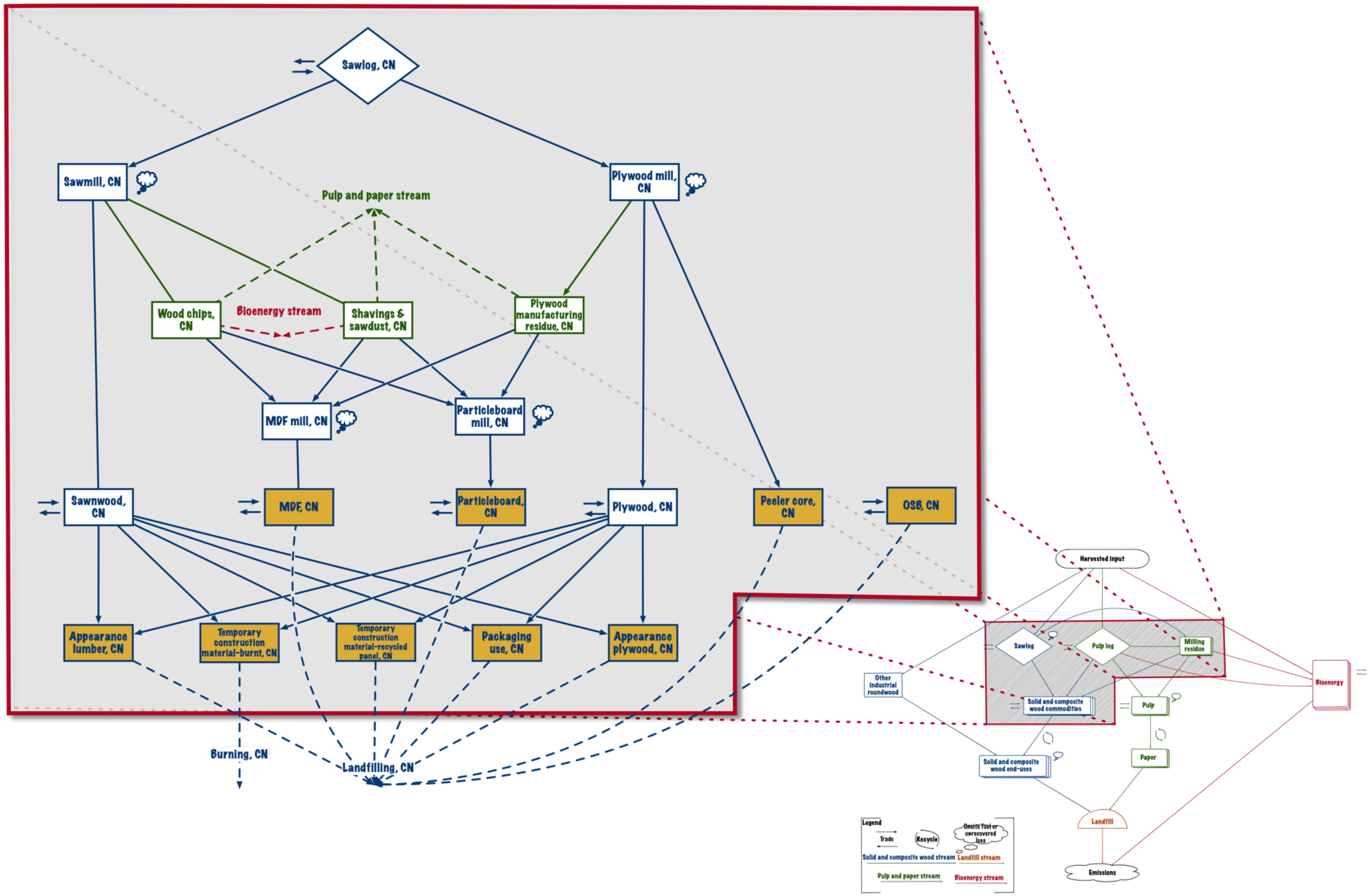

Figure 24. Detailed carbon flow of the solid and composite wood products stream in China.

The “temporary construction material” application is similar to the category of “industrial production” in Fig. 17. These temporary construction material uses are not structural or non-structural wood applications in wood constructions. Examples are scaffolding, concrete forming and pallets. They are burnt or recycled at the end of their life. The first order decay function was used to describe the carbon retention pattern of HWP end-uses in China [92, 101] and Tbl. 4 summarized the half-lives for each end-use. Appearance lumber and plywood generally lasted longer with a medium service life compared to the other uses. MDF and particleboard are used for similar applications in China (e.g., as furniture) and they have medium service lives. However, due to a lack of data, their end-uses cannot be further specified. The example end-uses of peeler cores are mop handles and photo frames. Although there are some pilot projects, developers in China generally do not build timber constructions. Consequently, the Chinese market does not produce a significant amount of OSB with imported BC wood. OSB in China is mostly used in similar applications to plywood.

Table 4. End-uses in China and their half-lives.

End-uses	Half-lives
Temporary construction material, burnt after use	0.5
Temporary construction material with recycle	2.5
Packaging use	3
Appearance lumber	35
Appearance plywood, OSB, MDF and particleboard	25
Other short-lived uses	2

2.2.8 Carbon allocations in the MitigAna model for this study

The MitigAna model used both static and dynamic carbon allocations. In the static carbon allocation process the carbon partition in a value adding or trading event was held constant for the study period whereas in the dynamic carbon allocation process the carbon partition varied over the study period. Whether static or dynamic carbon allocation was applied depended on the mitigation scenario modeled. In the following chapters, different market growth and policy implications were examined and these resulted in dynamic carbon allocations being applied to assess the impacts of these variables. However, technological advancement in wood products processing was not the focus of this study and therefore, static partitions were applied throughout all manufacturing processes. For example, based on the volumetric flow analysis conducted for this study (Appendix A), in BC’s sawmills on average 46% of the industrial roundwood volume under bark ended up as sawnwood, 39% ended up in the form of chips and 15% was produced as sawdust [35]. These volume partitions were used as the carbon allocation parameters for the sawmilling process and the values were held constant from 2016 to 2050 in Ch. 3. On the other hand, according to the scenario that was evaluated, the harvested biomass was utilized differently and the export volumes varied over time to fulfill the different levels of construction and bioenergy demand required by the scenario. In these cases, dynamic carbon allocations were used to vary the mixture of products manufactured, utilized and traded. For example, the export partitions of sawlogs varied between 10% in 2016 and 3% in 2050 in one of the domestic-market-prioritized scenarios.

Dynamic carbon allocations should increase the accuracy of the simulation results if the time series data are available, especially when the project is modeling the fate of carbon for reporting purposes. However, it may also increase the complexity of the model. In a mitigation analysis, if certain allocation events are not the focus, introducing a time series for these allocations may underestimate or overestimate the impact of the studied mitigation effort because these allocation events may increase or decrease oppositely to the allocations that are of interest.

A volumetric flow analysis was conducted with the goal of capturing the partitioning information in percentage form for the MitigAna model (see Appendix A). The analysis was conducted using the data compiled from BC's mill reports [35], Statistic Canada's International Merchandise Trade Database [190, 191, 278], wood products life cycle analyses [279–282] and forest products conversion factors [283]. The dynamic carbon allocations used in the numerous mitigation scenarios evaluated in this study are described in individual chapters that investigate these scenarios.

The harvest projections used in this study came from BC FLNRORD which is the same dataset used by Xu et al. [83]. The scope of this study was limited to the production, trade and usage decisions along the post-harvest wood products supply chain. This study did not explore alternative forest management and timber harvest strategies and therefore the harvest projections were held constant among the nine HWPs mitigation scenarios in the later chapters. This study also did not explore alternative uses of bark as a feedstock for liquid biofuel fuel production and assumed that it can only be used as hog fuel, because published literature indicates that high bark contamination in feedstocks can significantly reduce the yield of liquid biofuels [185]. Consequently, emissions from hog fuel combustion of 245 $MtCO_2e$ between 2016 and 2050 (on average 7 $MtCO_2e$ $year^{-1}$) were the same for all nine scenarios. Hog fuel emissions were not included in the scenario comparisons in the later chapters. Under bark data were used for carbon allocations, in accordance with the industrial roundwood data published by FAOSTAT and BC's mill report [35, 276].

2.3 Conclusions

The MitigAna model is a state-of-the-art harvested wood products carbon dynamics model developed in this study for mitigation analysis. It defined the carbon flow for British Columbia's harvested wood products in explicit stages including end-uses, constrained the biomass flow with a utilization hierarchy, modeled the residential renovation using a novel approach to avoid overestimating carbon retention, implemented the Gamma distribution to better estimate the carbon retention pattern and updated the service lives according to the latest research findings. The MitigAna model can be used to quantitatively evaluate a range of biomass trade and utilization scenarios for BC.

3 Inward- versus Outward-Focused Bioeconomy Strategies for British Columbia's Forest Products Industry: A Carbon Storage and Emission Perspective

3.1 Background

Much of the world is seeking to combat the threat of climate change and to achieve Sustainable Development Goals (SDGs), such as ensuring access to sustainable modern energy and building sustainable cities and communities [284, 285]. Different jurisdictions possess widely divergent levels of resources and may have to find different solutions to sustainable energy and low impact construction techniques.

The province of British Columbia (BC) in Canada is well endowed with forest resources as it contains 55 million hectares (Mha) of forests and has one of the largest forest areas per capita in the world: 11.2 ha per person [33, 34]. In comparison, the global average is only 0.55 ha per person [34]. These forests provide climate mitigation opportunities for BC that many other jurisdictions do not have and they are expected to contribute to meeting the province's and the nation's emission reduction targets.

Forests contribute to emission reduction by removing atmospheric carbon (C) through photosynthesis and storing C in all components of a tree and in the soil [12, 286]. Humans harvest wood from the forest and process the biomass into harvested wood products (HWPs). C is locked up in these HWPs until they are decomposed or combusted. Simultaneously, new trees continue to grow and store C in the forests. Depending on the type of HWP manufactured and the use of these products, the C pools in HWPs may effectively delay the release of C to the atmosphere [24]. The size of the HWP C pool fluctuates depending on the service time and society's consumption capacity of HWPs [270, 287].

In BC, the majority of the C in the harvested roundwood is converted into HWPs with the provincial wood products manufacturing processes typically having about 1% unrecoverable material loss and 32% of the input C being used to provide process energy [35]. Therefore, most C harvested from BC's forests is stored in HWPs for a certain period of time depending on their use (see Section 2.2.3.2 and 2.2.7). With time, most of the C stored in HWPs will eventually be emitted back to the atmosphere, with the exception of some extreme cases such as wooden temples that may stand for over a thousand years (e.g., the Pagoda of Fogong Temple in China, Horyu-ji Temple in Japan, Greensted Church in England, and Urnes Stavkirke Stave Church in Norway) or non-degradable C when wood is buried in landfills [288–290]. Simultaneously to the HWP carbon being emitted to the atmosphere, well-managed forests regenerate and remove carbon from the atmosphere. Depending on the service lives of wood products and the forest regeneration rate, these events may result in net carbon removals from or additions to the atmosphere. Sustainable management practices and woody biomass utilization strategies should aim to achieve the former. If the input to the HWP C pools is larger than the C emitted back to the atmosphere, the HWP C pools will grow and net removals from the atmosphere will occur. These HWP C pools may eventually reach saturation, at which point the input to the pools will equal the output to atmosphere. However, it is uncertain when the C pools will saturate because it is uncertain whether the demand for wood products will become constant, higher or lower in the future. A decrease in HWP inputs may result in the pools saturating more quickly, while an increase may result in them being a sink for a longer time. The longer wood products can delay the release of carbon while forests remove more C from the atmosphere, the greater the chance of attaining a net removal from the atmosphere. Thus, sustainable forest management in combination with the use of long-lived wood products can contribute to net removals from the atmosphere. However, many factors affect the gains and losses of carbon from forests and harvested wood product carbon pools and therefore careful quantification of ecosystem C dynamics and C dynamics in HWP pools need to be conducted and compared to a business-as-usual scenario to determine whether or not a particular forest sector mitigation strategy is climate effective.

Several authors have suggested that the best practice from a C perspective is to manage the forest sustainably, while continuously supplying society with harvested woody biomass [12, 24, 291, 292]. Harvesting and replanting are ways to maintain strong C sinks in the forest. The rates of forest growth are strongly age-dependent and, depending on the forest type and other factors, younger trees remove C at higher rates than older trees [24].

This study is part of the Forest Carbon Management Project funded by the Pacific Institute of Climate Solutions (PICS) [42]. The project has a broader objective and examines forest sector mitigation options and interactions with climate change. This chapter specifically addresses harvested wood biomass utilization strategies in BC. More specifically, it focuses on the production, trade and usage decisions along the post-harvest wood products supply chain. The chain begins when harvested biomass is removed from the forest and turned into commercial products such as industrial roundwood. The ecosystem carbon dynamics, including forest regrowth and decay of logging residues left on site are addressed in other analyses (e.g., [42]) but are outside the scope of this study.

As a consequence of reduction in growing stocks from the impacts of the Mountain Pine Beetle and large-scale forest fires in recent years, BC is anticipating reduced roundwood harvest for the next decades [34, 39]. In contrast, population and wood demand are projected to grow for the same period for both BC and its major trading partners [293–295]. On the other hand, ambitious climate targets have incentivized many other sectors such as the aviation and long-range transportation sectors, and these sectors are considering the increased use of renewable forest biomass in their GHG emission reduction strategies [181, 183, 296]. As a result, forest biomass may become a limited resource that will need to be utilized as efficiently as possible to maximize its contribution to climate change mitigation. Moreover, as BC is considering the development of a bioeconomy with potentially significant increases in wood consumption, choices related to the allocation of harvested wood to long-lived products (e.g., in the building sector) or to bioenergy (e.g., liquid transportation fuels in the transportation sector) can also affect the GHG balance in the forest sector and in other sectors inside and outside of BC.

BC is a net exporter of wood products; 90% of the forest products were sold to the international markets in 2018. Approximately 60% of the solid wood products and wood composites production was exported to the United States (US); 50% of the pulp and paper production was exported to China; and 80% of the wood pellet production was sent to the European Union (EU) countries. In contrast, the domestic market[3] only consumes 10% of BC's total wood products production [35, 76, 297]. Under the current internationally agreed "production approach" GHG emissions reporting rule, BC is responsible for reporting emissions arising from biomass that was harvested in BC, regardless of where in the world the HWP emission occur [47, 48]. However, importing countries can utilize BC's wood very differently. Consequently, the rates of carbon retention and therefore potential climate benefits vary significantly among different trade and utilization strategies. This chapter seeks to analyze the GHG emission consequences of inward- vs outward-focused scenarios for BC's HWPs.

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[3] "Domestic market" means the market of BC and other provinces in Canada. To restrict the biomass origin to BC and avoid ambiguity, domestic demand or domestic consumption in this article refers to wood products that are harvested in BC and demanded or consumed in BC and other provinces of Canada.

3.2 MITIGATION SCENARIOS USED IN THIS STUDY

In this study, the goal of the mitigation analysis was to examine the *potential* contribution of BC's harvested wood products to reduce GHG emissions. The mitigation scenarios for this type of analysis may be designed from a variety of perspectives, such as environmental, economic, social or a mixture of different viewpoints.

The scenarios considered in this chapter were designed from a carbon perspective, which is a subcategory of the environmental viewpoint. For some of the scenarios, the economic or social constraints were intentionally pushed to extreme conditions to provide an indication of a potential range of outcomes (i.e., bounding of upper and lower ends of the range of values). These extreme conditions were then adjusted to provide some more realistic scenarios that delivered more meaningful outcomes to the policy community.

The 9 scenarios used in this study are summarized in Tbl. 5.

Table 5. Mitigation scenarios used in this study.

Mitigation scenarios	Abbreviation
1. Baseline scenario	BASE
2. Extreme scenarios	
2.1 All harvested biomass manufactured to construction material	ALL_CONS
2.2 All harvested biomass used as feedstock for renewable fuel	ALL_FUEL
3. Inward-focused scenarios	
3.1 Domestic demand increase driven by population	IN_POP
3.2 Increase domestic market share of timber construction	IN_CONS
3.3 Prioritize renewable fuel feedstock	IN_FUEL
4. Outward-focused scenarios	
4.1 Prioritize export to US and other markets for construction	OU_CONS
4.2 Prioritize export to China	OU_CN
4.3 Prioritize export to EU for energy	OU_EU

Each of these scenarios is described in the following sections.

3.2.1 BASELINE SCENARIO (BASE)

The business-as-usual baseline scenario assumed that the domestic consumption versus trade partitions, and production efficiencies remained constant from 2016 to 2050 [35, 76, 278].

An example of domestic consumption versus trade partitions follows. According to the most recent data, 9% of BC's total sawnwood production was consumed domestically and 91% was exported

[278]. In the BASE scenario, these partition values (i.e., 9% vs. 91%) were assumed to be constant from 2016 to 2050.

As an example of the production efficiencies, average BC forest products manufacturing data indicated that 47.6% of the saw log volume under bark was converted into sawnwood, 38.1% to wood chips and 14.3% to sawdust [35]. In the BASE scenario, these yield partitions (i.e., 47.6%, 38.1% and 14.3%) were assumed to be constant from 2016 to 2050. In addition, all the carbon allocations to forest products manufacturing sub-categories were estimated using 2016's production and trade data, assumed to be constant from 2016 to 2050, and configured in the same fashion in the model as the above examples.

3.2.2 Extreme scenarios

Extreme scenarios were designed to demonstrate the extreme upper- and lower-bounds of the magnitude of HWPs carbon storage and the associated size of various wood products markets. The purpose of these scenarios was to evaluate the range of impacts possible using various HWPs utilizations when developing a climate change mitigation strategy. These scenarios did not seek to predict the amount of future GHG emissions and they should not be viewed from this perspective. Instead, when the results of more realistic scenarios were compared to the outcome of these extreme scenarios, these boundary conditions helped to quantify the degree of achievement accomplished by the realistic mitigation efforts relative to the theoretical extreme, and to identify additional efforts that could be made to move closer to the theoretical potentials.

3.2.2.1 All forest biomass manufactured to construction materials (ALL_CONS):

In general, wood used in construction has a longer service life compared to other applications such as industrial uses, paper products and bioenergy (see Section 2.2.3.2 and 2.2.7). This scenario assumed that all harvested biomass was manufactured into construction materials. Consequently, all sawlogs were sent to sawmills or plywood mills. Pulp logs were sent to oriented strand board (OSB) mills. Milling residues such as wood chips and sawdust were sent to medium density fiberboard (MDF) mills and particleboard mills. In this scenario, there was no fiber input for the pulp and paper mills nor for bioenergy feedstocks external to manufacturing processes. The only bioenergy consumption was onsite combustion of manufacturing byproducts (e.g., approximately 8% of the wood input for OSB and MDF manufacturing that is combusted in the form of wood chips, sawdust or shavings) for process energy. Sawnwood, plywood and OSB were assumed to be used for structural construction uses or structural repair and remodeling. MDF and particleboard were assumed to be used to build non-structural components, such as kitchen cabinets, kitchen and bathroom counters, doors and mouldings.

This scenario sought to quantify the maximum carbon storage that could be achieved in theory by BC's wood-based bioeconomy, without considering market, production capacity, financial or technology constraints, and ignoring any leakage. This scenario also indicated the housing market demand that would be needed to achieve this theoretical maximum carbon storage.

3.2.2.2 All forest biomass as feedstock for renewable fuels (ALL_FUEL):

This scenario assumed that all harvested biomass was used as a feedstock to produce renewable gasoline, diesel and jet fuel. For simplicity, this study has not assumed a technological barrier for the "drop-in" biofuels, the scenarios could be applied for any 35-year period from once the technology has become available. As the carbon in wood fuels is conventionally treated as instantaneously oxidized, this scenario was equivalent to emitting all the harvested carbon to the atmosphere as CO_2 in the year of harvest. The mitigation benefit of using wood as a fuel therefore arose only from the substitution effect. Since wood resources are renewable and the carbon emitted from wood can be re-captured by the forest, if wood-based renewable fuels are used to displace the use of fossil fuels, it may help achieve the goal of decarbonization. However, given that the energy density of wood-based biofuels is lower than fossil fuels, this strategy may initially cause an increase in emissions and require long payback times [159–161]. The substitution benefits of wood-based renewable fuel and wood as a construction material are addressed in Ch. 4.

The goal of this scenario was to quantify the minimum theoretical carbon storage and to determine whether BC's woody biomass was sufficient to satisfy BC's transportation fuel demand.

3.2.3 INWARD-FOCUSED SCENARIOS

As the name suggests, inward-focused scenarios prioritize consumption by the domestic market over international trade. In this scenario, the only exports were those HWPs that remained after the domestic demand was satisfied. The export partitions to different jurisdictions stayed the same as for the BASE scenario. For example, of the 91% of BC's sawnwood exported, 65% was shipped to the US, 21% to China, 8% to Japan and 6% to all the other regions [278]. These partitions did not change in the inward-focused scenarios even though the export volumes were decreased.

BC has long been a major net exporter of wood products and consequently the role of BC's HWPs in emission reductions is expected to be strongly affected by the policies and behaviors of the various export markets. The scenarios under this category aimed to quantify the potential significance of the domestic market from a carbon perspective.

3.2.3.1 Domestic demand increase driven by population (IN_POP):

Canada's population is projected to increase over the coming decades. In general, HWPs demand correlates with population size [94, 293, 294]. This scenario assumed the demand for domestic HWPs increased in proportion to population growth [298]. The IN_POP scenario was the basis for all inward- and outward-focused scenarios, meaning that the increased domestic demand for various HWPs due to population growth has the priority to be satisfied first.

3.2.3.2 Increase domestic market share of timber construction (IN_CONS):

Housing completions in general follow the trend of household formation [293]. This scenario therefore assumed that the domestic demand of residential dwellings increased in proportion to household growth.

Non-residential buildings also usually increase as communities grow larger. Consequently, the domestic demand of the non-residential buildings was assumed to also increase proportionately with household growth.

In Canada, roughly 30% of the residential dwellings and 10% of the non-residential buildings are built with wood, although these shares are larger in BC at approximately 50% of residential and 25% for non-residential [80–82]. For comparison, wood accounts for 97% of all framing material and 64% of floor construction in residential dwelling constructions in the US [134]. Given the similarities between the US and Canadian market and construction culture, the domestic timber construction market has some significant potential that hasn't been realized. In additional, the Wood First program and the international promotion of mass timber tall wood buildings should also strengthen future market growth of timber constructions [299–301]. This scenario assumed that the timber construction market share could be doubled between 2017 and 2050 in the domestic market.

3.2.3.3 Prioritize renewable fuel feedstock (IN_FUEL):

Forty percent (40%) of the emissions in BC and 24% of the emissions in Canada come from the transportation sector [10, 302]. There have been substantial investigations into the use of forest biomass to produce renewable fuels in BC [61, 181, 296, 303].

Sawnwood and plywood are produced from sawlogs which are normally considered too valuable to be used directly as an energy feedstock. Milling residues, such as wood chips and sawdust, are economically more suitable for this task. Additionally, 6% to 10% of wood residues are burnt onsite during production to provide energy [35]. Pulp logs may be commercially feasible to use directly as a feedstock for bioenergy [70]. This scenario assumed that the remaining pulp logs and milling residues after fulfilling the domestic demand in the IN_POP scenario were used as a bioenergy feedstock to produce renewable gasoline, diesel and jet fuels while sawnwood and plywood production and market partitions remained unchanged.

3.2.4 Outward-focused scenarios

Under the circumstances of a projected declining harvest amount and a growing population [39, 298], these scenarios assumed that BC's forest sector fulfilled the domestic market demand in the IN_POP scenario first and then wood products were allocated to foreign regions. The emission consequences and mitigation implications of these options were explored in the following set of scenarios.

3.2.4.1 Prioritize export to US and other markets for construction products (OU_CONS):

The United States imports 60% of BC's solid wood and wood composites, and is by far BC's largest importer [75, 278]. China imports 20% of BC's solid wood and wood composites and 50% of BC's pulp and paper products, and is BC's second largest importer [190, 278]. EU imports over 80% of BC's wood pellets [278]. The US uses a large proportion of wood as construction material and the timber construction market share is one of the highest in the world [84, 134]. China, on the other hand, mostly uses wood for short-lived applications such as concrete casing and packaging [92]. The EU mostly combusts BC's pellets for heat and electricity [70].

Despite the diverse utilization practices, these markets all have a size that can potentially consume a great amount of BC's wood as construction materials. The US has a construction market that is 7 times larger than Canada's [304]. China has one that is over 30 times larger [305], whereas the EU has one that is about 8 times larger [306, 307].

This scenario assumed that all the HWPs remaining after fulfilling the domestic demand were exported and used as construction materials. Sawnwood, plywood and OSB produced from sawlogs or pulp logs were mainly used as structural material. The milling residues were burnt onsite to provide energy, or manufactured into MDF and particleboard for non-structural applications such as cabinets, kitchen and bathroom counters, doors and moldings.

3.2.4.2 Prioritize export to China (OU_CN):

China replaced Japan and became the second largest importer of BC wood products after the Global Financial Crisis in 2008. The principal products imported by China are raw logs, sawnwood and chemical pulp [190, 278, 308]. The end uses of BC's wood in China are mostly shorter-lived categories such as paper, concrete casing, shipping and packaging [92].

This scenario assumed that the HWPs remaining were exported to China after fulfilling the domestic demand, and the HWPs production and consumption partitions in China remained the same.

3.2.4.3 Prioritize export to EU for energy (OU_EU):

The European Union has been actively committed to switching to renewable energy. Targets have been set to increase the share of renewables in energy consumption to 20% in 2020 and 27% by 2030 [64]. While no specific share percent has been set for 2050, it has been estimated that in order to achieve a low-carbon economy by 2050, the EU countries would need to triple their current level of bioenergy consumption and the feedstock may largely come from the agricultural and forestry sectors [309]. One of the EU's options is to import wood pellets primarily from Canada and the US [70, 310].

The European Union has been the largest consumer of BC wood pellets with an import share of over eighty percent [278]. The EU's pellet demand will continue to rise if they decide to rely heavily on wood-based bioenergy as one of the major renewable energy sources.

This scenario assumed that after fulfilling the domestic demand the remaining forest biomass was manufactured into wood pellets and exported to EU countries. This assumption involved sending the remaining sawlogs, pulp logs and milling residues to pellet mills.

3.2.4.4 Reasons to exclude changes to Japanese market from the scenarios:

Japan is currently the third largest importer of BC wood, accounting for 8% of BC's harvested volume, which is only equivalent to about 12% of the imports of US or 38% of China and is slightly larger than all the other jurisdictions combined.

On the other hand, Japan's population continues to decline, and unlike the other trading partners, the indicators of the Japanese construction sector are relatively weak [94, 274]. BC is also not the primary source of Japan's pulp and paper imports and Japan is not anticipated to use large quantities of wood for energy.

Although Japan is still an important market for BC, it is less likely to play a major part in BC's future low-carbon bioeconomy strategy. For this reason, mitigation scenarios were not designed to include future changes to the Japanese market.

3.3 RESULTS

The Methods section (Sec. 3.6) is placed after the conclusions. This Results section describes the HWPs carbon mitigation implications of the nine scenarios outlined in the above section.

3.3.1 BASELINE SCENARIOS (BASE)

Under the BASE scenario, BC's harvest gradually declined from 60 $MtCO_2e$ $year^{-1}$ in 2016 to 51 $MtCO_2e$ $year^{-1}$ in 2050, with a cumulative transfer of carbon from forests to the product sector of 1.9 $GtCO_2e$. In this scenario, 74% of the carbon in HWPs produced after 2016 (roughly 1.4 $GtCO_2e$) would be emitted to the atmosphere over the period of 2016-2050, with the remainder 26% (approximately 0.5 $GtCO_2e$) staying in the HWPs (Fig. 25). In reality, an additional amount may be stored in the landfills but this study treated landfilled woody biomass as instantaneous emissions, consistent with the way in which Canada's GHG Inventory is reported [46]. The rate of carbon accumulation in the pool slowly decreased over the study period (from 33 $MtCO_2e$ $year^{-1}$ in 2016 to 7 $MtCO_2e$ $year^{-1}$ in 2050 as demonstrated by the carbon storage (grey series) in Fig. 25). Carbon losses from the harvest prior to 2016 were not reported here because this study examined future mitigation scenarios and the inherited emissions were the same for all scenarios. The annual emissions of carbon from wood harvested since 2016 increased over time (from 26 $MtCO_2e$ $year^{-1}$ in 2016 to 44 $MtCO_2e$ $year^{-1}$ in 2050). The increase of emissions from 2016 to 2020 was mainly due to emissions within China and US, with emissions in the other regions staying relatively constant. The Chinese emissions largely arose because the weighted average service life of wood in China was about 7 years. The amount emitted in the US during this period mainly came from wood used in industrial production such as pallets, concrete casings, and paper products. These applications had short service lives. Annual emissions increased steadily and slowly from solid wood and wood composites within US and Canada. Geographically, the largest emissions occurred within Canada with 85% of the domestic emissions originating from burning black liquor, a by-product generated during kraft pulp production, which is burnt on-site to recycle chemicals and provide electricity and heat. Chemical pulp dominated BC's pulp manufacturing with 95% of the fiber input sent to chemical pulp mills [35]. China imported less than half of the roundwood equivalents than the US, but the emissions from wood harvested since 2016 were roughly the same as those in the US because of China's short-lived wood utilization practices.

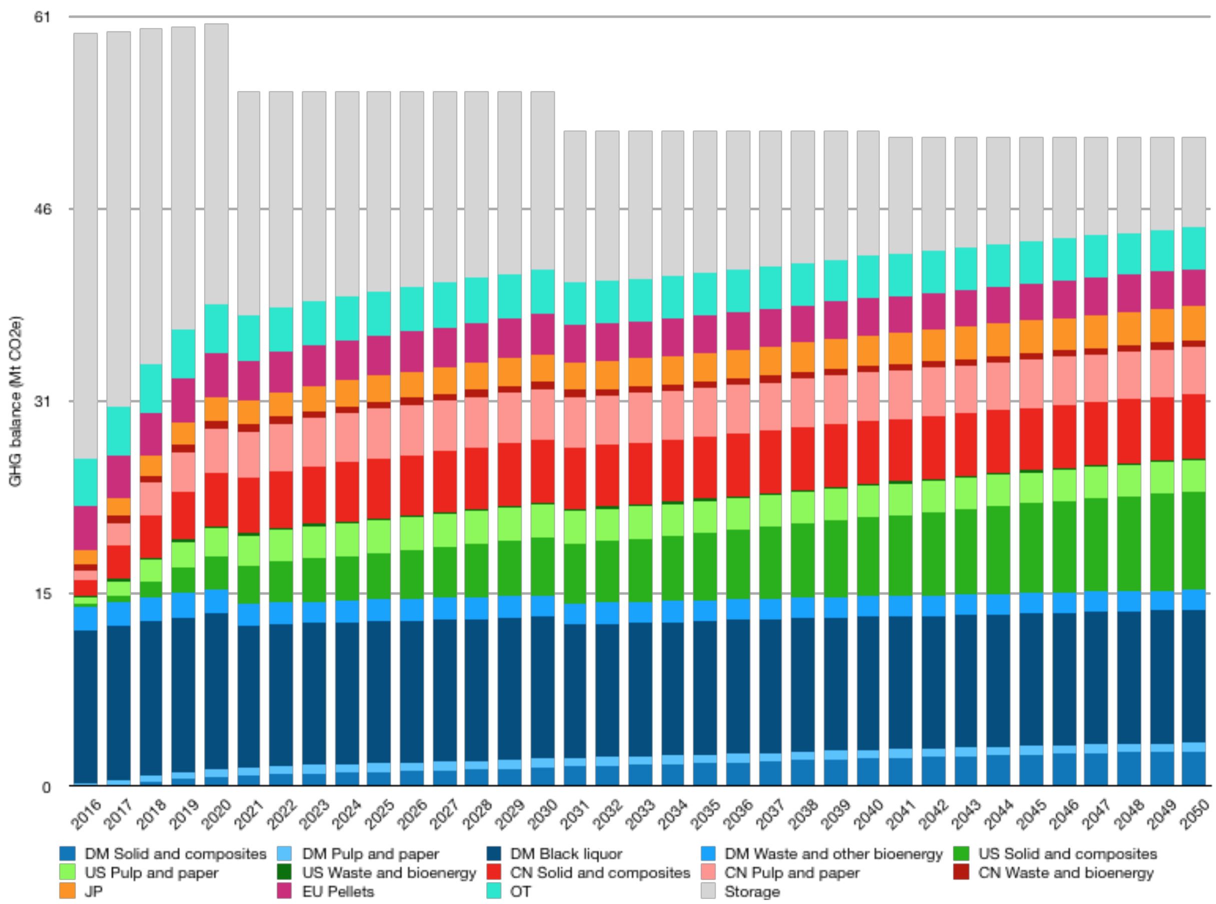

Figure 25. Annual GHG balance of HWPs harvested in BC from 2016 to 2050 of the BASE scenario. Blue series are emissions from HWPs consumed domestically (DM); greens - US; reds - China (CN); orange - Japan (JP); pink - EU; cyan - other jurisdictions (OT); grey is the amount added to the net carbon storage (i.e., total annual harvests minus total annual emissions from products harvested since 2016).

3.3.2 ALL FOREST BIOMASS MANUFACTURED TO CONSTRUCTION MATERIALS (ALL_CONS)

If all of BC's harvested biomass was used for construction, there would be a substantial delay in carbon release (Fig. 26). In this scenario, the annual carbon storage ranged from 33 $MtCO_2e$ $year^{-1}$ in 2016 to 53 $MtCO_2e$ $year^{-1}$ in 2050. The carbon stored in these structures would slowly release back to the atmosphere. In 2050, 79% (1.5 $GtCO_2e$) of the C harvested since 2016 was still remaining in products. Annual emissions ranged from 6.1 $MtCO_2e$ $year^{-1}$ in 2021 to 19 $MtCO_2e$ $year^{-1}$ in 2050, with a cumulative emission reduction of 72% compared to the BASE scenario. There were some immediate carbon releases of approximately 3 $MtCO_2e$ $year^{-1}$ due to unrecovered losses or onsite wood-based bioenergy combustion during manufacturing.

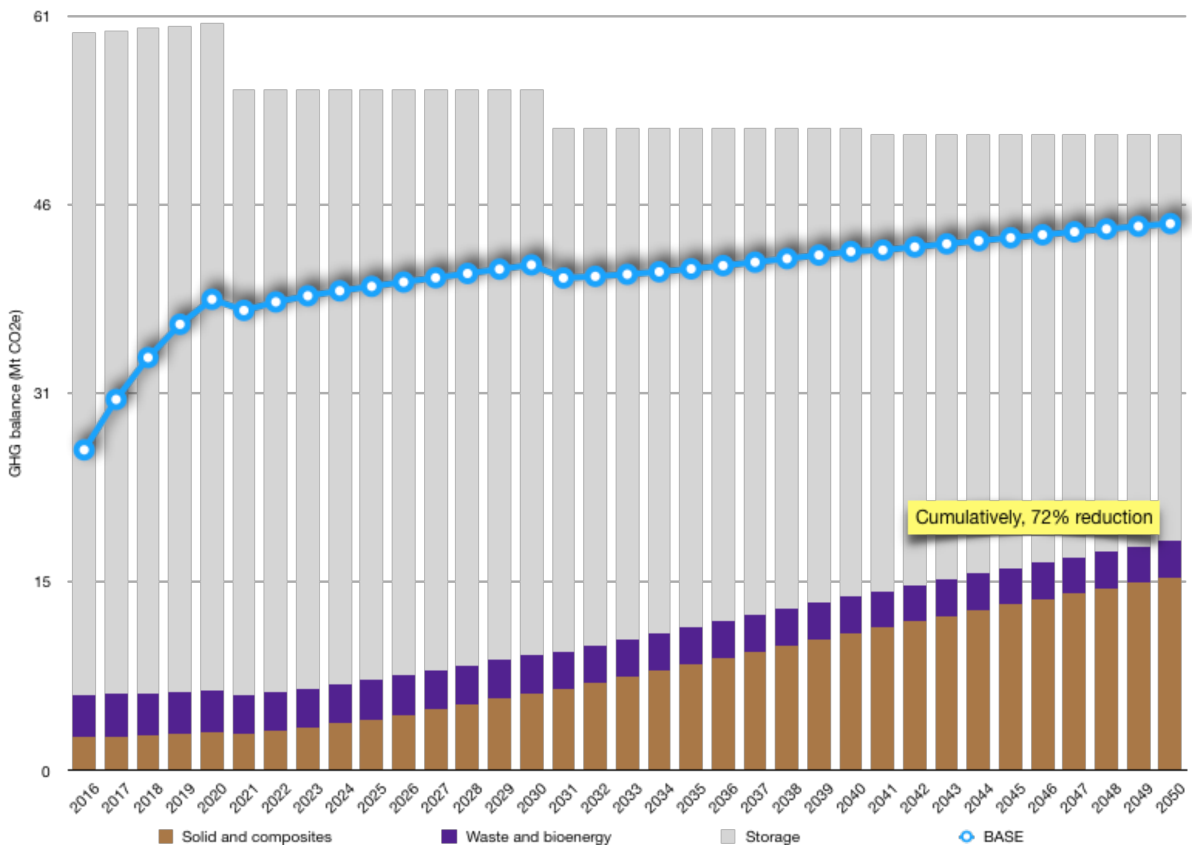

Figure 26. Annual GHG balance of BC's HWPs from 2016 to 2050 of the ALL_CONS scenario. Brown is the emissions from solid woods and wood composites in constructions including renovation; purple is emissions from sawdust and shavings burnt as energy or unrecovered losses during HWPs manufacturing; grey is the amount added to the net carbon storage (i.e., total annual harvests minus total annual emissions from products harvested since 2016); blue line with markers is the total emissions of the BASE scenario listed here for comparison; yellow text box indicates the cumulative difference compared to the BASE scenario.

3.3.3 ALL FOREST BIOMASS AS FEEDSTOCK FOR RENEWABLE FUELS (ALL_FUEL)

In this scenario, all harvested carbon was released back to the atmosphere in the year of harvest because all biomass was used as feedstock for renewable gasoline, diesel and jet fuel (Fig. 27). The quantity emitted equals the harvest amount which averaged 54 $MtCO_2e$ $year^{-1}$ for the period 2016-2050. There is no carbon storage in this scenario, therefore cumulatively 1.9 $GtCO_2e$ were released to the atmosphere from burning of wood-based renewable transportation fuels. These fuels were expected to off-set fossil fuels and the substitution effects are addressed in Ch. 4.

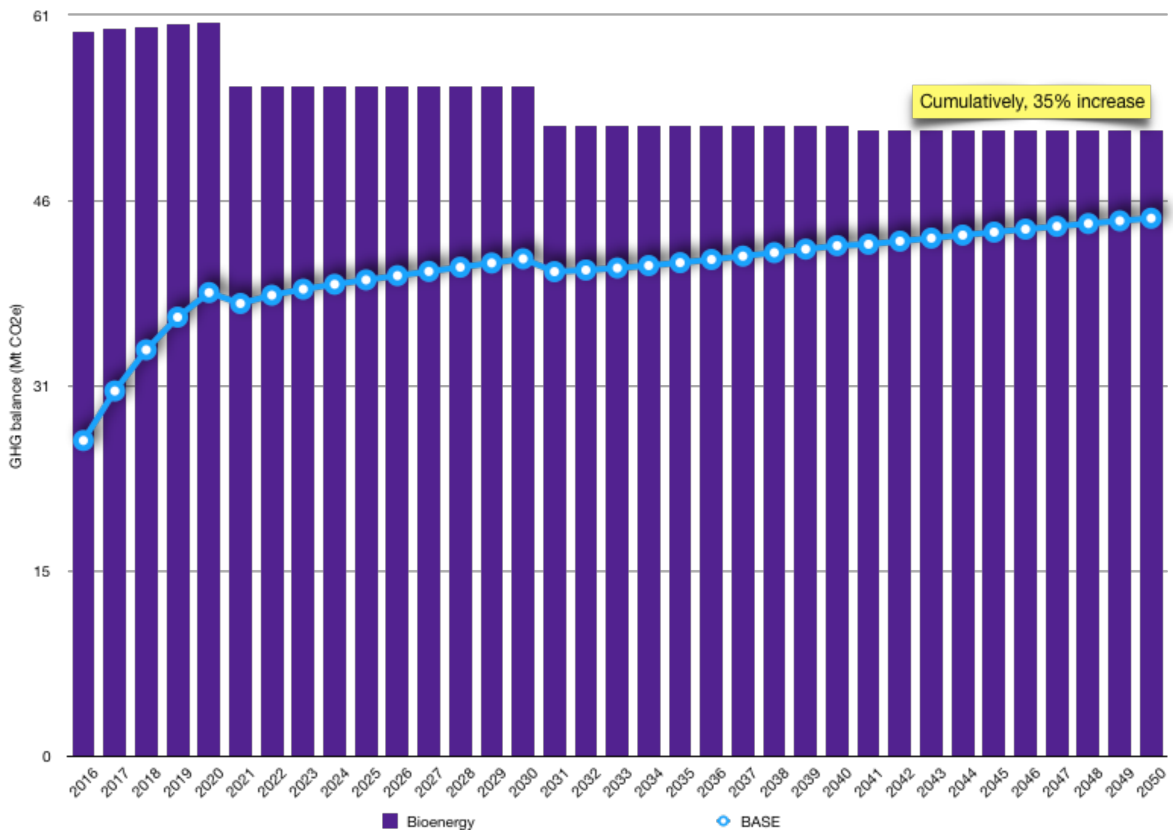

Figure 27. Annual GHG balance of HWPs harvested in BC from 2016 to 2050 of the ALL_FUEL scenario. Purple is emissions from renewable jet fuel, diesel and gasoline combustion; blue line with markers is the total emissions of the BASE scenario listed here for comparison; yellow sticky note indicates the cumulative difference compared to the BASE scenario.

3.3.4 Domestic demand increase driven by population (IN_POP)

The IN_POP scenario followed a similar HWPs emission trajectory to the BASE scenario (Fig. 28, cf. Fig. 25). The annual emissions ranged from 26 $MtCO_2e$ year^{-1} in 2016 to 42 $MtCO_2e$ year^{-1} in 2050, slightly less than the BASE scenarios. The largest domestic emission source remained black liquor combustion as the structure of BC's pulp industry did not change. Cumulatively, there was a 6% emission reduction compared to the BASE scenario which was caused by the increased domestic demand that shifted exports to domestic consumption. Saw log exports reduced from 10% to 2% and all the pulp logs were consumed domestically. The largest importer of BC's raw logs continued to be China and the HWPs service lives in Canada were longer than in China which consequently reduced the emissions. A small proportion of OSB and graphics paper was shifted to be consumed domestically. These products however had only minor effects on emission reductions.

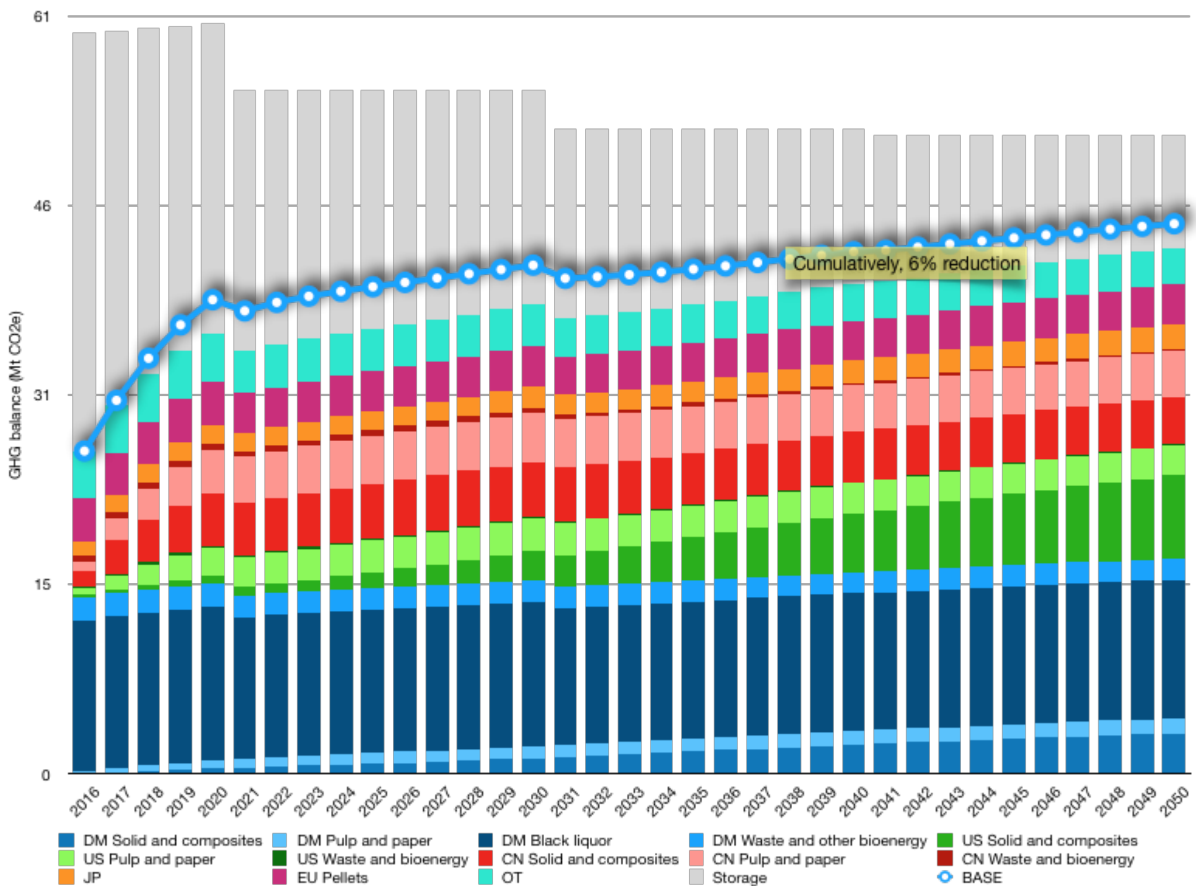

Figure 28. Annual GHG balance of HWPs harvested in BC from 2016 to 2050 of the IN_POP scenario. Blue series are emissions from HWPs consumed domestically (DM); greens - US; reds - China (CN); orange - Japan (JP); pink - EU; cyan - other jurisdictions (OT); grey is the amount added to the net carbon storage (i.e., total annual harvests minus total annual emissions from products harvested since 2016); blue line with markers is the total emissions of the BASE scenario listed here for comparison; yellow text box indicates the cumulative difference compared to the BASE scenario.

3.3.5 *Increase Domestic Market Share of Timber Construction (IN_CONS)*

In this scenario, all the sawlogs and pulp logs were consumed domestically to produce solid wood and wood composites to meet the increased demand in the construction sector. In addition, some sawnwood, plywood, OSB and MDF were shifted from export markets to meet the domestic demand. The general emissions trajectory of this scenario is similar to the BASE and IN_POP scenarios. The annual emissions ranged from 26 MtCO$_2$e year^{-1} in 2016 to 41 MtCO$_2$e year^{-1} in 2050 (Fig. 29). The domestic emissions were slightly higher but lower in the other jurisdictions, especially China. Cumulatively, there was a 10% reduction compared to the BASE scenario.

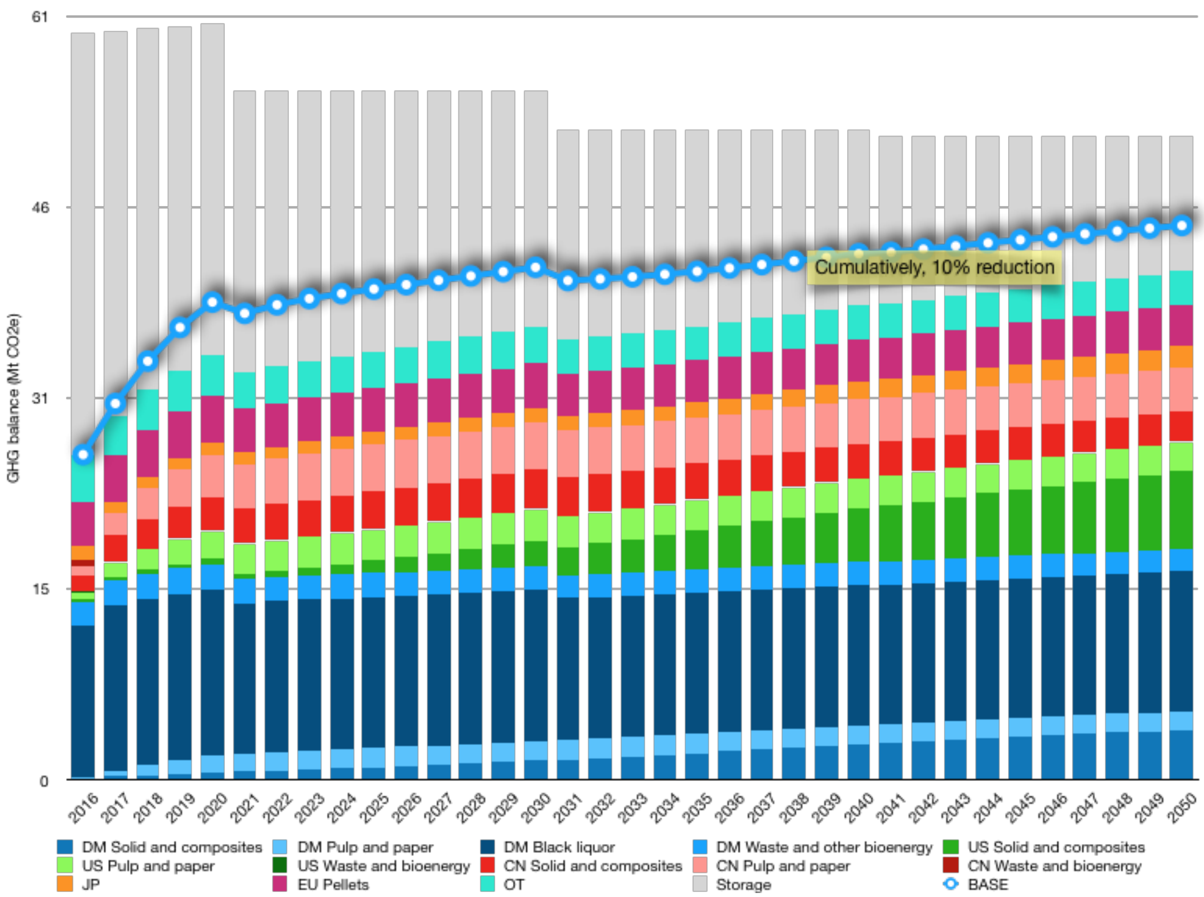

Figure 29. Annual GHG balance of HWPs harvested in BC from 2016 to 2050 of the IN_CONS scenario. Blue series are emissions from HWPs consumed domestically (DM); greens - US; reds - China (CN); orange - Japan (JP); pink - EU; cyan - other jurisdictions (OT); grey is the amount added to the net carbon storage (i.e., total annual harvests minus total annual emissions from products harvested since 2016); blue line with markers is the total emissions of the BASE scenario listed here for comparison; yellow text box indicates the cumulative difference compared to the BASE scenario.

3.3.6 Prioritize renewable fuel feedstock production (IN_FUEL)

In this scenario, BC produced renewable transportation fuels using the remaining pulp logs and milling residues after fulfilling the domestic demand for various other HWPs. The annual emissions ranged from 35 $MtCO_2e$ $year^{-1}$ in 2016 to 44 $MtCO_2e$ $year^{-1}$ in 2050 (Fig. 30). A proportion of the carbon previously emitted from short-lived end-uses in the export markets was now emitted from the renewable fuels consumed in the domestic market.

Although the *domestic* emissions increased, wood-based renewable jet fuel, diesel and gasoline were expected to displace conventional jet fuels, diesel and gasoline and achieve emission reductions through the substitution effect. The climate benefits of renewable fuels displacing fossil fuels have been studied by several life cycle assessments (LCA) (e.g., [185, 197, 208, 210]) and the quantitative benefit for BC will be estimated in Ch. 4. That being said, the total emissions in this scenario were 0.3% lower than the BASE scenario, not including the substitution benefits from the displacement of fossil fuels.

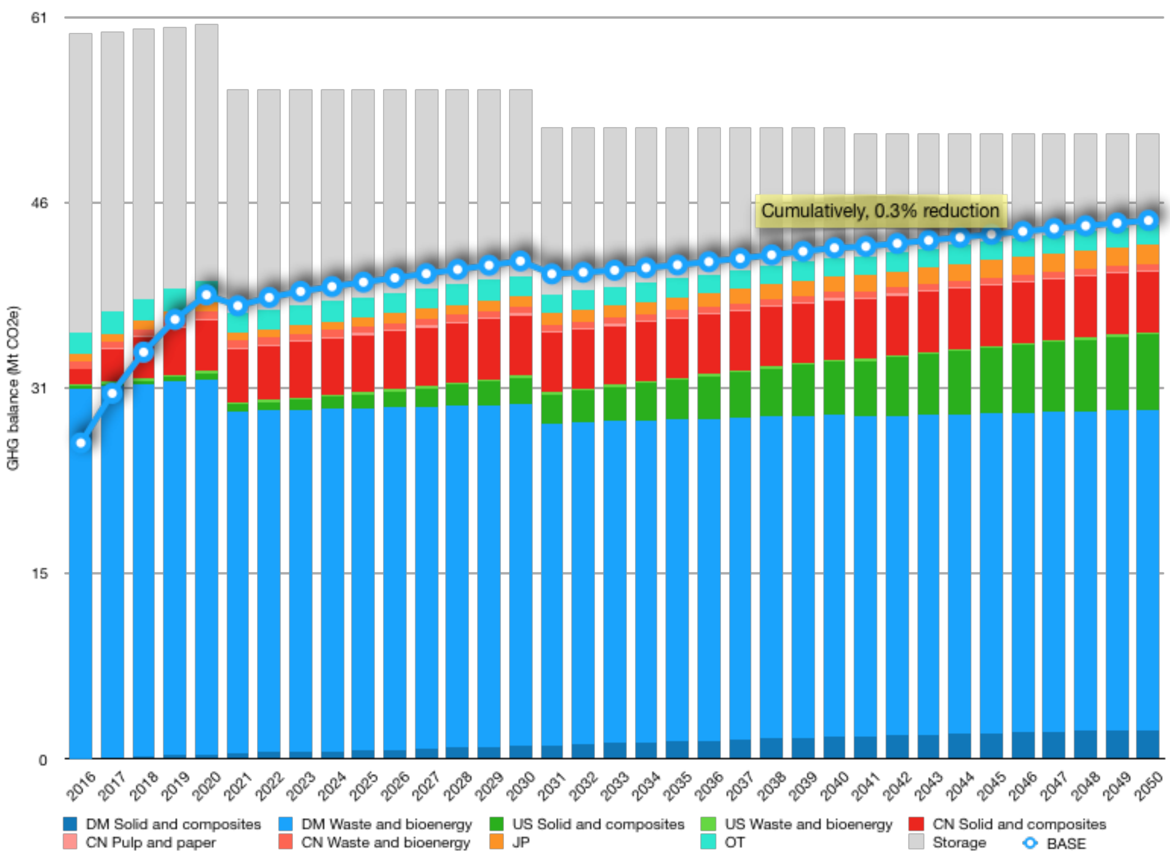

Figure 30. Annual GHG balance of HWPs harvested in BC from 2016 to 2050 of the IN_FUEL scenario. Blue series are emissions from HWPs consumed domestically (DM); greens - US; reds - China (CN); orange - Japan (JP); no emissions in EU; cyan - other jurisdictions (OT); grey is the amount added to the net carbon storage (i.e., total annual harvests minus total annual emissions from products harvested since 2016); blue line with markers is the total emissions of the BASE scenario listed here for comparison; yellow text box indicates the cumulative difference compared to the BASE scenario.

3.3.7 PRIORITIZING EXPORTS TO US AND OTHER MARKETS FOR CONSTRUCTION (OU_CONS)

In this scenario, excess woody biomass, which is the biomass remaining after fulfilling the demands of the domestic market, was manufactured into solid wood and wood composite products which were used as construction materials in export markets. The annual emission ranged from 8 $MtCO_2e$ $year^{-1}$

in 2016 to 19 $MtCO_2e$ $year^{-1}$ in 2050 (Fig. 31). In 2050, 74% (1.4 $GtCO_2e$) of the C harvested since 2016 had been added to the HWP pool under this scenario.

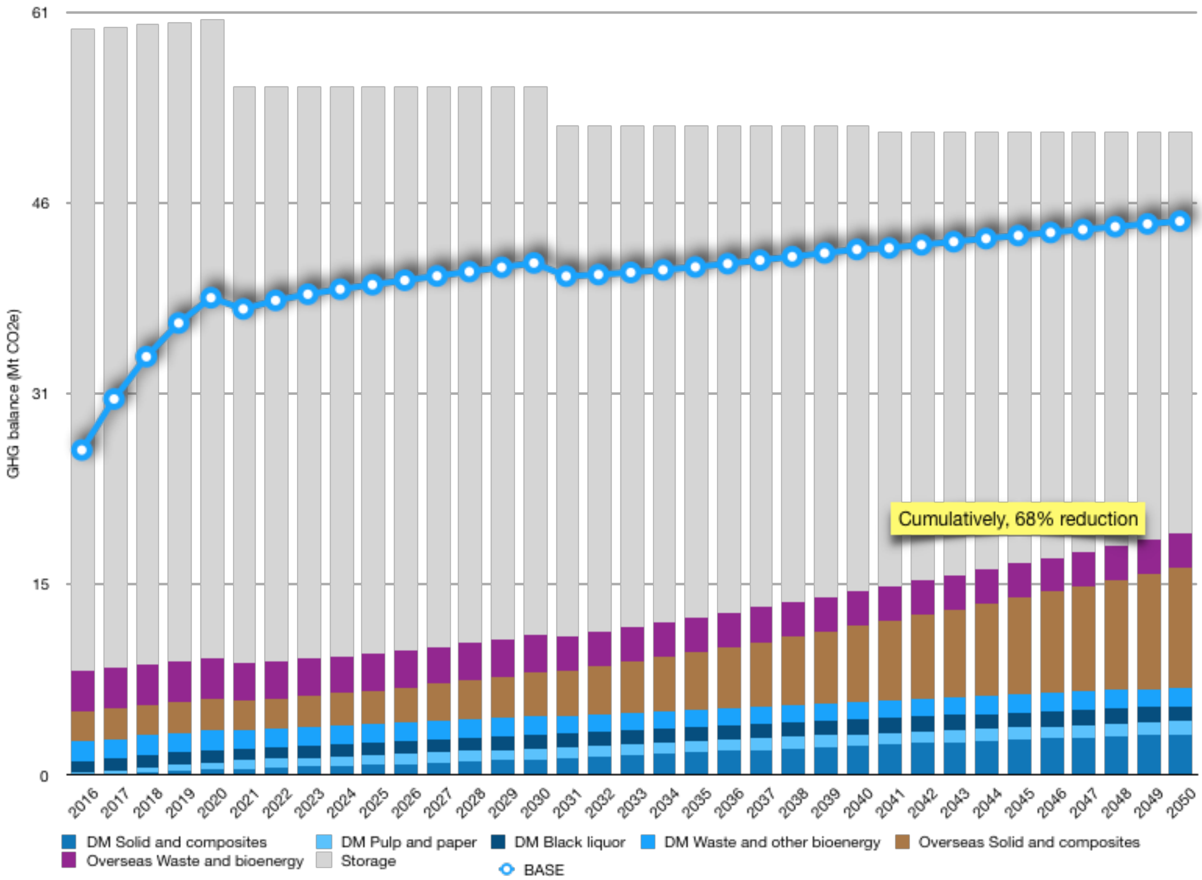

Figure 31. Annual GHG balance of HWPs harvested in BC from 2016 to 2050 of the OU_CONS scenario. Blue series are emissions from HWPs consumed domestically (DM); brown is the foreign emissions from solid woods and wood composites in constructions including renovation; purple is foreign emissions from sawdust and shavings burnt as energy or unrecovered losses during HWPs manufacturing; grey is the amount added to the net carbon storage (i.e., total annual harvests minus total annual emissions from products harvested since 2016); blue line with markers is the total emissions of the BASE scenario listed here for comparison; yellow sticky note indicates the cumulative difference compared to the BASE scenario.

3.3.8 *Prioritizing exports to China (OU_CN)*

In this scenario, HWPs after fulfilling the domestic market demand were exported to China. Wood in China is primarily used for short-lived purposes such as paper, concrete casing, pallets and shipping packages [92]. In this scenario, the annual emissions ranged from 24 $MtCO_2e$ $year^{-1}$ to 47 $MtCO_2e$ $year^{-1}$ (Fig. 32). Emissions in China increased compared to the BASE scenario as expected due to the increased consumption, and these increased emissions need to be reported in BC's GHG inventory in which emissions from all wood harvested in BC are included, regardless of where in the world they occur. The emissions in year 2016 were lower than those in the BASE scenario because in the OU_CN scenario BC did not produce any wood pellets for export to the EU. Instead, it produced more solid and composite wood products for short-lived applications and more chemical pulp for the Chinese market. The half-lives of these products in China were approximately 2 to 3 years [47, 92]. Therefore the emissions were higher than the BASE scenario in 2017. More chemical pulp production also resulted in additional emissions from black liquor within BC.

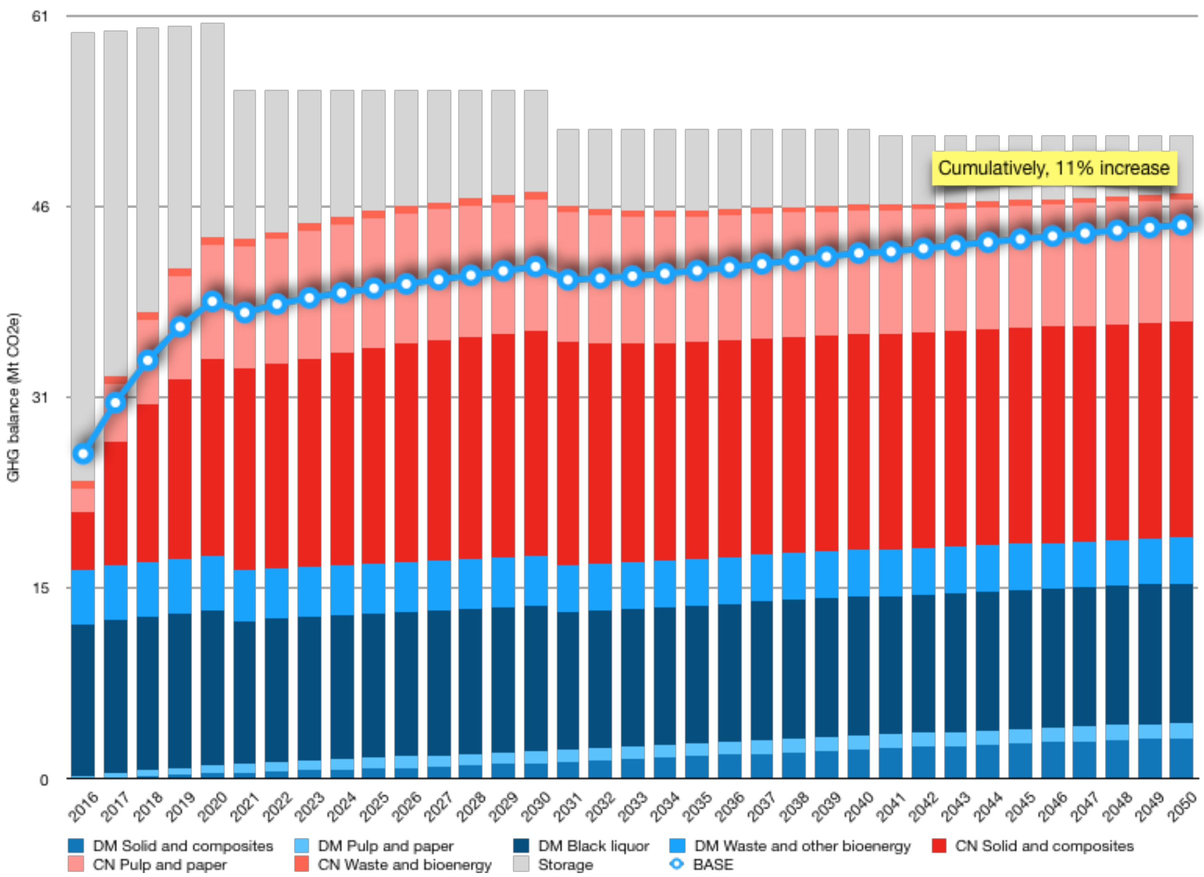

Figure 32. Annual GHG balance of HWPs harvested in BC from 2016 to 2050 of the OU_CN scenario. Blue series are emissions from HWPs consumed domestically (DM); no emissions in US; reds - China (CN); no emissions in Japan; no emissions in EU; no emissions in the other jurisdictions; grey is the amount added to the net carbon storage (i.e., total annual harvests minus total annual emissions from products harvested since 2016); blue line with markers is the total emissions of the BASE scenario listed here for comparison; yellow text box indicates the cumulative difference compared to the BASE scenario.

3.3.9 *PRIORITIZING EXPORTS TO EU FOR ENERGY (OU_EU)*

In this scenario, the forest biomass remaining after fulfilling the domestic market demand was used to produce wood pellets for the EU. The EU could potentially consume up to approximately 26 Mt of wood pellets from Canada [70]. In this scenario, BC produced about 21 Mt of wood pellets. The annual emissions decreased from 54 $MtCO_2e$ $year^{-1}$ in 2016 to 49 $MtCO_2e$ $year^{-1}$ in 2050 due to the declining harvest (Fig. 33). All the carbon storage occurred in the domestic regions. There was no foreign carbon pool because only wood pellets were exported and carbon in wood pellets was assumed to be emitted in the year of harvest. The associated emissions are reported in BC's GHG inventory, while the fossil fuel emission reductions are reported in the country that uses the pellets [311]

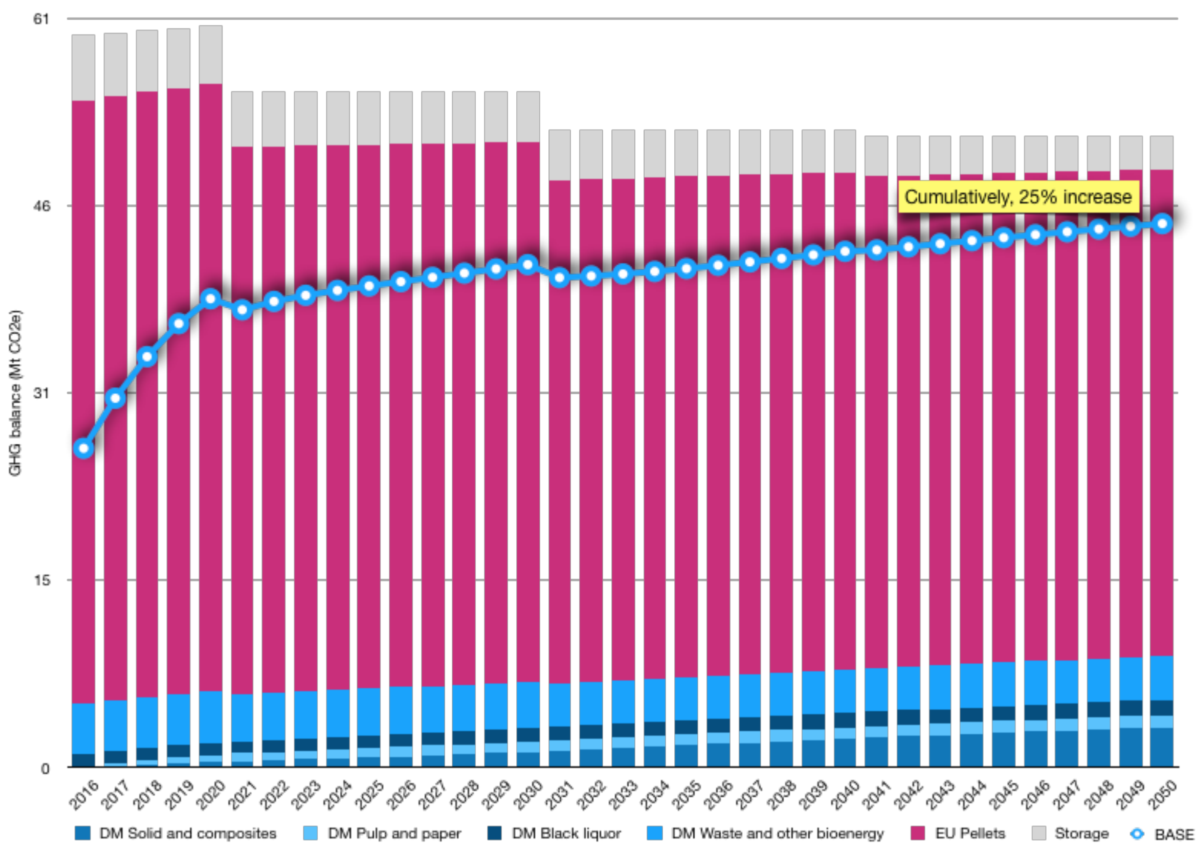

Figure 33. Annual GHG balance of HWPs harvested in BC from 2016 to 2050 of the OU_EU scenario. Blue series are emissions from HWPs consumed domestically (DM); no emissions in US; no emissions in China; no emissions in Japan; pink - EU; no emissions in the other jurisdictions; grey is the amount added to the net carbon storage (i.e., total annual harvests minus total annual emissions from products harvested since 2016); blue line with markers is the total emissions of the BASE scenario listed here for comparison; yellow text box indicates the cumulative difference compared to the BASE scenario.

3.3.10 COMPARISONS

Fig. 34 summarizes the annual emission differences of all mitigation scenarios relative to the BASE scenario and Fig. 35 shows the cumulative emission differences. Scenarios that prioritized short-lived HWP utilizations emitted more than the BASE scenario. Scenarios that promoted HWPs as long term construction materials (i.e., scenarios with the suffix of "_CONS") achieved greater mitigation benefits. The inward-focused scenarios emitted less than the BASE scenario. The gaps of annual emissions among all scenarios were narrowing over time as carbon was slowly emitted back to the atmosphere (Fig. 34). This was also observed in the cumulative figure as the slopes of the curves are declining over time (Fig. 35).

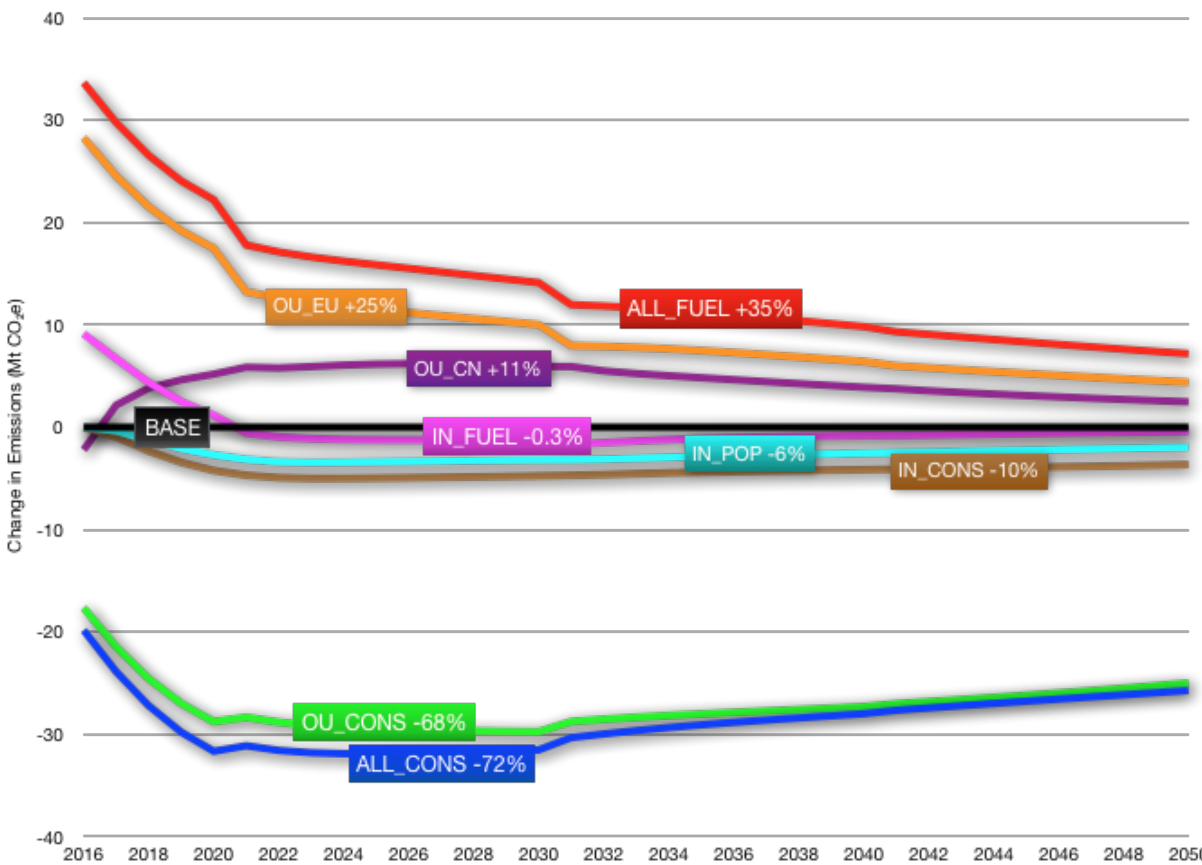

Figure 34. Annual emission differences of all mitigation scenarios relative to the BASE scenario. The black line at y = 0 indicates the BASE scenario. All scenario names are defined in Tbl. 5.

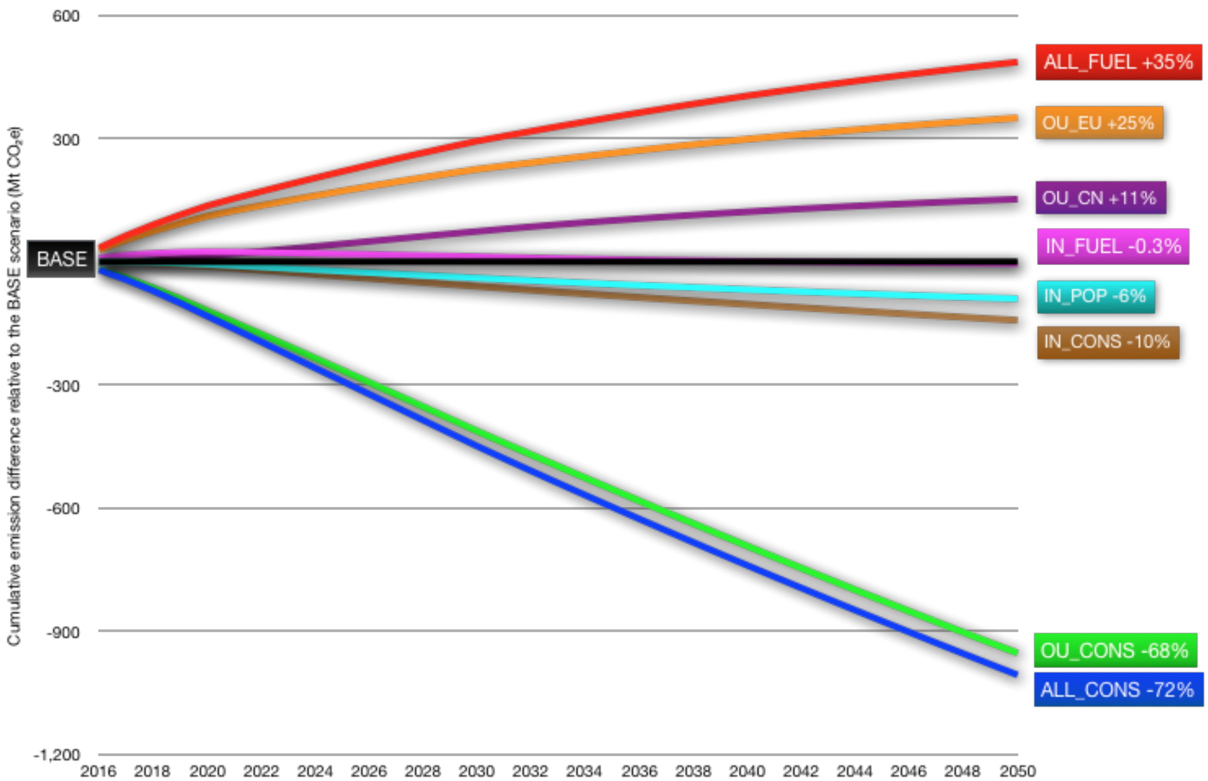

Figure 35. Cumulative emission differences of all mitigation scenarios relative to the BASE scenario. The black line at y = 0 indicates the BASE scenario. All scenario names are defined in Tbl. 5.

The detailed emission consequences of each scenario can be more easily compared by evaluating time points at year 2020, 2030, 2050 and by aggregating the emissions from 2016 to 2050 (Fig. 36).

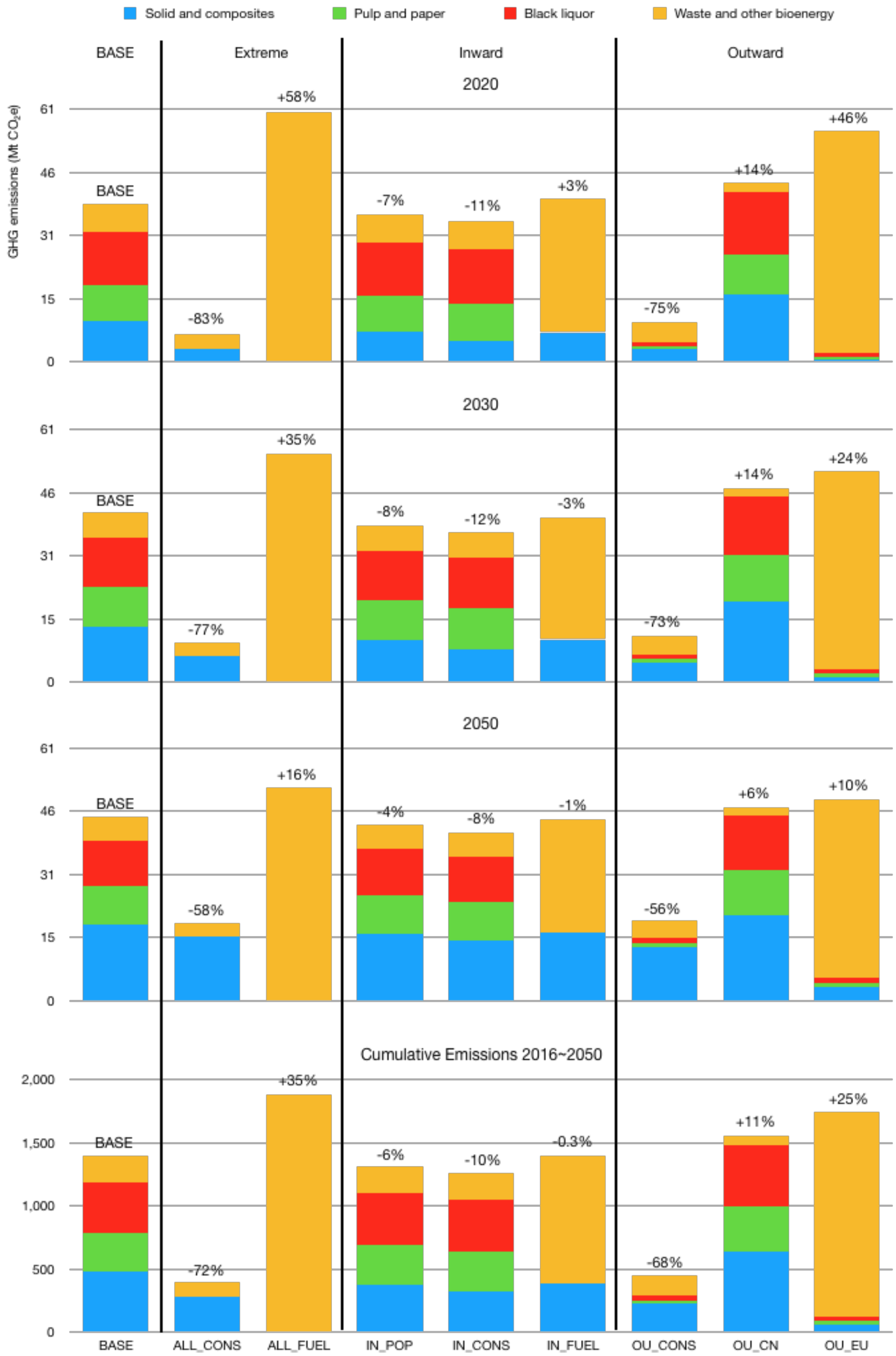

Figure 36. A comparison of the emission consequences of the 9 scenarios designed in this study at year 2020, 2030, 2050 and cumulative emissions from 2016 to 2050. The +/- percentage numbers on top of the bars are emissions changes compared to the BASE scenario.

The ALL_CONS scenario achieved the lowest emissions among all 9 scenarios studied (Figs. 34-36). This scenario generated the lowest emission possible in theory from BC's HWPs, because all the harvested forest biomass was allocated to wood products processing facilities to produce structural and non-structural products for construction. Therefore, except for onsite energy use in the form of wood chips, sawdust and shavings, most carbon was stored in timber constructions. Cumulatively, this scenario emitted 391 $MtCO_2e$ which was 72% less than the 1.4 $GtCO_2e$ emitted by the BASE scenario (Fig. 36: ALL_CONS and BASE in Cumulative Emissions 2016~2050). The emissions of the ALL_CONS scenario gradually increased over time from 6.5 $MtCO_2e$ in 2020 to 18.6 $MtCO_2e$ in 2050, as the carbon stored in timber construction was slowly emitted to the atmosphere due to renovation and demolition (as indicated by the increases in the blue bars of the ALL_CONS scenario from 2020 to 2050 in Fig. 36). It is worth noting that these were emissions from wood harvested since 2016. Emissions from wood harvested prior to 2016 will be decreasing over the same period. These inherited emissions will be the same for all scenarios as the scenarios only affected future carbon allocations. They do not affect the difference between scenarios and were not reported here. Although the emissions almost tripled between 2020 and 2050, they were still much lower than the average 40 $MtCO_2e$ $year^{-1}$ annual emissions in the BASE scenario. Achieving this lowest emissions scenario would require the use of HWPs to annually construct buildings with floor areas of 154 million m^2 $year^{-1}$, which is equivalent to constructing on an annual basis approximately 10,000 Brock Commons Tallwood House,[4] which is an 18-story hybrid mass timber construction. However, BC wood currently was used to construct only 30 million m^2 $year^{-1}$: 3 million m^2 $year^{-1}$ domestically and 27 million m^2 $year^{-1}$ abroad [80–82, 134, 314]. For comparative purposes, in 2016, China has annual residential housing starts of 2 billion m^2 $year^{-1}$ (equivalent to 112,000 Brock Commons) [305]; US has 177 million m^2 $year^{-1}$ (equivalent to 12,000 Brock Commons) [315]; Canada has 32 million m^2 $year^{-1}$ (equivalent to 2,100 Brock Commons) [307]; BC has 8 million m^2 $year^{-1}$ (equivalent to 520 Brock Commons) [314]; the UK has 3 million m^2 $year^{-1}$ (equivalent to 200 Brock Commons) [316]. The wood frame market shares of single-family houses and low- to mid-rise buildings in the US and Canada are relatively high already [80–82, 134], but further potential exists to increase the quantities of wood used for high-rise residential buildings, non-residential buildings and public infrastructures in both regions. The timber construction market share in China is extremely low but the authorities

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[4] the calculation is based on wood volume. Brock Commons used 2233 cubic meters of CLT and Glulam [312, 313]. This scenario sends roughly 21 million cubic meters of sawnwood to construction sites on an annual basis. Detailed calculation are presented in in Appendix B.

have shown interest in exploring options to increase wood construction [94]. It is noteworthy that even a small market penetration in China, such as 10%, would mean an achievement of the 154 million m^2 $year^{-1}$ (equivalent to 10,000 Brock Commons) demand required in the ALL_CONS scenario.

While the ALL_CONS scenario generated the lowest possible emissions, the ALL_FUEL scenario resulted in the largest possible emissions from BC's HWPs as all carbon was emitted in the same year of harvest. These two scenarios provided the upper and lower emission bounds. In the ALL_FUEL scenario, the emissions gradually declined over time from 60 $MtCO_2e$ $year^{-1}$ in 2020 to 51 $MtCO_2e$ $year^{-1}$ in 2050 in accordance with the harvest projections (Fig. 36: ALL_FUEL in 2020 and 2050). Cumulatively, this scenario emitted 1.9 $GtCO_2e$ within the study period, which was 35% more than the BASE scenario (Fig. 36: ALL_FUEL in Cumulative Emissions 2016-2050).

The ALL_FUEL scenario also helps determine whether there is enough forest biomass to satisfy BC's demand for renewable transportation fuels. The CleanBC plan sets a biofuel production target of 650 million liters by 2030 [60]. Our calculation indicates that there is ample forest biomass in BC to achieve this target (Appendix C Renewable transportation fuel calculation). However, this biofuel target is only 8% of the fuel demand of BC's transportation sector. In order to satisfy the fuel demand of the province's entire transportation sector, BC would need to consume all of its harvested biomass for renewable fuel production and even then fuel production would fall about 1% short of the current demand. For further context, BC's demand is only 13% of Canada's transportation fuel requirements[5].

The IN_POP scenario achieved a cumulative 6% decrease in emissions compared to the BASE scenario (Fig. 36: IN_POP in Cumulative Emissions 2016-2050). With the exception of US (34 years), the weighted average service lives of HWPs in Canada (32 years) are generally longer than those of China (6 years), Japan (24 years), EU (0 years) and other importers, which led to the emission reductions observed. The emission reductions were higher in 2020 at 7% but declined to 4% in 2050. This was because renovations usually occur at around 30 years of service life and a considerable amount of BC's HWPs were used for renovation purposes. Therefore, slightly more

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[5] The energy demand of BC's transportation sector is 334.45 PJ and Canada's is 2601.13 PJ [317]. The energy content of renewable fuel is 35.6 MJ L^{-1} and the fuel yield is roughly 12.5 kJ (g forest biomass)$^{-1}$ [185, 208, 318]. Detailed calculations are presented in Appendix C.

carbon from solid and composite wood products was released after 2045 than in the BASE scenario (Fig. 28). The greater domestic demand for construction materials also increased the production of milling by-products and residues, which led to slightly increased emissions from waste, bioenergy and pulp and paper.

As expected, the IN_CONS scenario achieved the lowest emissions among the three inward scenarios (Fig. 36: IN_CONS in Cumulative Emissions 2016~2050), because this scenario doubled the domestic timber construction market share. Cumulatively, this scenario achieved a 10% emission reduction compared to the BASE scenario. The emission reduction is higher in 2020 at 11% and declined to 8% in 2050. This trajectory is the same as the IN_POP scenario because HWPs for renovation purposes were approaching their end-of-life around 2045.

Unexpectedly, the IN_FUEL scenario did not increase the HWP emissions. Compared to the BASE scenario, the emissions were only higher for the period before 2020 and became lower thereafter (Fig. 30). More specifically, there was a 3% emission increase in 2020 and a 1% decrease in 2050 (Fig. 36: IN_FUEL in 2020 and 2050). The cumulative emissions were actually 0.3% less than the BASE scenario (Fig. 36: IN_FUEL in Cumulative Emissions 2016-2050). This was because of the configuration of the scenarios. As described in the earlier section, inward- and outward-focused scenarios all assumed meeting the domestic demand in the IN_POP scenario for various products first (i.e., the domestic demand was assumed to increase in proportion to population growth). In the IN_FUEL scenario, sawlogs were still primarily used to produce sawnwood and plywood for both domestic and international markets. The remaining pulp logs, milling by-products and residues were allocated for renewable fuel production after fulfilling the domestic demand for various other products. Increased domestic demand driven by population growth shifted some HWPs from foreign markets to be consumed domestically, similar to the IN_POP scenario. The emission reduction caused by this shift slightly outweighed the increased emissions associated with biofuel combustion.

The renewable fuel produced in the IN_FUEL scenario can meet also meet CleanBC plan’s 650 million liters target but can only cover half of the energy demand of BC’s transportation sector or seven percent of the demand of Canada’s transportation sector. Since saw logs are not normally used as a feedstock for renewable fuel, the renewable fuel produced in this scenario is the largest output amount that is theoretically feasible for BC.

The OU_CONS scenario resulted in a cumulative emission of 444 $MtCO_2e$, which was a reduction of 68% compared to the BASE scenario (Fig. 36: OU_CONS in Cumulative Emissions 2016-2050). The emission reduction is higher in 2020 at 75% and declined to 56% in 2050, which is the same trajectory as the IN_POP and IN_CONS scenarios due to emissions arising from HWPs that were subject to renovation. This scenario required BC's trading partners to use BC wood products to build a wood construction floor area of 140 million m^2 $year^{-1}$ (equivalent to about 9,000 Brock Commons). This number is approximately 75% of the US housing starts or 8% of the Chinese housing starts in terms of floor area [304, 305].

The Chinese and EU's markets are large but generated 11% and 25% more emissions respectively compared to the BASE scenario, due to their shorter-lived uses of wood (Fig. 36: OU_CN and OU_EU in Cumulative Emissions 2016~2050). Notably, emissions were higher in these scenarios than the IN_FUEL scenario. This observation was due to the IN_FUEL scenario assuming that sawnwood and plywood were predominantly exported to the US for relatively longer-lived uses, whereas the OU_CN and OU_EU scenarios prioritized China and EU as export destinations which had shorter service lives for the imported commodities.

3.4 DISCUSSION

British Columbia's substantial forest resources provide mitigation opportunities that are not available to many other jurisdictions and the mix of wood products manufactured can have a significant influence on BC's future biogenic emission profile (Fig. 36). More specifically, scenarios that extended the service lives of HWPs (i.e., ALL_CONS, IN_POP, IN_CONS and OU_US) resulted in lower emissions than those that focused on short term uses (i.e., ALL_FUEL, IN_FUEL, OU_CN and OU_EU). The largest cumulative emission difference between scenarios of 1.5 $GtCO_2e$ occurred when the two boundary scenarios, ALL_CONS and ALL_FUEL, were compared (Fig. 36: the difference between ALL_FUEL and ALL_CONS in Cumulative Emissions 2016~2050). However, the boundary values estimated in these extreme scenarios are not an indication of the future emission profile. The more practical scenarios using population and market capacity bases produced a lower cumulative emission difference of 493 $MtCO_2e$ between the IN_CONS and OU_EU scenarios which is approximately one third of the cumulative emission difference of the two extreme scenarios. For comparison, BC's emissions from HWPs (not accounting for the compensating sinks in forests) and from all sectors except forestry are about 40 $MtCO_2e$ $year^{-1}$ and 60 $MtCO_2e$ $year^{-1}$, respectively [10]. The IN_CONS scenario resulted in 36 $MtCO_2e$ $year^{-1}$ emissions from HWPs in 2030 which is approximately 3 $MtCO_2e$ $year^{-1}$ lower than the 2007 level [10]. This more practical scenario that promoted wood as a low carbon building material compared well with the emission reductions target in the CleanBC plan [60] which specified a 2 $MtCO_2e$ $year^{-1}$ emission reduction by 2030 in the building sector. These reductions are achieved only through increased carbon retention in wood products, while additional emission reductions through the substitution of emissions-intensive building materials were not included here. Therefore, although the long-term strategy that focused on wood construction within Canada (i.e., the IN_CONS scenario) resulted in a smaller mitigation benefit than the IN_FUEL and OU_CONS scenarios, it can contribute meaningfully to BC's emission reduction goals.

The domestic HWP market only consumes about 15% of BC's harvests [35, 76, 278] and the inward strategies demonstrated mitigation potentials that were limited by the size of the domestic market. In general, the inward scenarios varied only by a ±5% difference. The foreign markets for HWPs are larger, however the emissions varied substantially depending on how the exported wood was used (Fig. 36: compare OU_CONS, OU_CN and OU_EU). The mitigation analysis indicated that, from the perspective of GHG emission reduction targets only, BC was better off consuming all harvested biomass domestically for various product demands including renewable transportation fuels, and only exporting wood for long-lived purposes, rather than short-lived applications (Fig. 36: OU_CONS and IN_FUEL). In the past decade, the share of BC's lumber in the US timber construction market has averaged 17% with the highest being 20% [94]. The US construction market is unlikely able to take all the exported wood outlined in the OU_CONS scenario. Therefore, if BC were to move to this more structural wood-prioritized bioeconomy, BC would have to rely on accessing both the US market and penetrating new international construction markets. China has the only other construction market with sufficient scale. The Canada–US Softwood Lumber Dispute and the Sino-Canada trade tensions may be major roadblocks for the realization of this bioeconomy plan. If there is not sufficient HWP demand in the foreign construction markets, this study showed that it may be better for BC to pursue renewable transportation fuel investment and substitute fossil fuels in the domestic market than to export to jurisdictions with short-lived wood product utilization practices. This was demonstrated by the IN_FUEL scenario resulting in lower emissions than the BASE, OU_CN and OU_EU scenarios (Fig. 36). Although the IN_FUEL scenario was a hypothetical scenario, since OSB, MDF and paper products were not produced, it revealed that exporting wood pellets, pulp logs and chemical pulp were not the best utilization of BC's forest resources from a biogenic emissions perspective. Wood pellets were exported to Europe to generate electricity. Pulp logs and chemical pulp were exported to China for paper making and other short-lived uses. However, wood-based renewable transportation fuel manufacturing of the type utilized in these models requires substantial further development to be technologically and economically feasible.

Another example of how HWPs may influence future emissions was shown by a consideration of the black liquor emissions from pulp manufacturing. Producing chemical pulp from BC's harvested biomass generated a significant amount of black liquor which emitted on average 11 $MtCO_2e$ $year^{-1}$

and cumulatively 402 $MtCO_2e$ over the study period (Fig. 36: red bars in the BASE scenario). Combusting black liquor reduces chemical pulp mills' dependency on fossil energy sources. However, the resulting paper product is still short-lived. These values would increase if more pulp was produced to fulfill the demands of the Chinese market (i.e., the OU_CN scenario). Pulp mills in BC may claim energy self-sufficiency and emission reduction achievements by using black liquor and wood residues to generate electricity under the assumption of carbon neutrality of bioenergy [53, 319]. However, from an atmospheric carbon perspective wood-based bioenergy is at best "carbon lean" instead of "carbon neutral" [29]. Moreover, BC's electricity can largely be generated by hydropower which has a lower climate impact than combusting wood-based bioenergy. Substituting hydropower with black liquor bioenergy provides little climate benefit, if any. This black liquor may be converted into liquid transportation fuel and displace fossil fuels [200, 320]. Notably, less than 10% of the black liquor emissions arose from pulp and paper production destined for domestic consumption. Over 90% of those emissions were associated with the production of pulp and paper for export[6]. That said, BC's pulp and paper sector contributes 1.5 billion dollars to the province's GDP on an annual basis and employs eight thousand people [79, 321–323].

Similarly, if BC was to develop a bioeconomy policy that only made long-lived products, such as structural lumber from sawlogs and non-structural panels from pulp log and residues, there would be a significant impact on international trade and this bioeconomy could fail economically. A forest industry with a diverse product portfolio provides resilience to the province's economy and communities. The prosperity of human society relies on wood to provide more than just long-term uses such as housing. Even if these social and economic implications were ignored, there would be substantial emission leakages if forest biomass was limited to long-term applications. If the world demands wood fibre for paper manufacturing, it is going to manufacture that product somewhere. Restricting pulp production and exports in BC will not eliminate these black liquor emissions on a global scale.

Wood product markets are demand-driven and may have conflict with environmental outcomes. Therefore, BC may wish to develop a utilization hierarchy to facilitate the achievement of the optimum emission reduction while achieving the desired economic outcomes. A utilization hierarchy

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[6] This point can be visualized in Fig. 36 by comparing the red bars in the BASE scenario (or IN_POP, IN_CONS, OU_CN) to the OU_CONS scenario (or OU_EU), because the OU_CONS and OU_EU scenarios assumed that only the domestic demand for pulp and paper were fulfilled.

would define a priority cascade based on the mitigation analysis results and advise the policy community to develop a hierarchical climate change mitigation incentive system, for example a hierarchical carbon credit system. Such a system would co-exist with the other market-drivers. However, in order to develop such a utilization hierarchy, mitigation analysis should go beyond biogenic emissions. Substitution effects of wood-based bioenergy compared to wood as a construction material should also be investigated and this topic will be addressed in Ch. 4.

3.5 Conclusions

British Columbia has substantial forest resources which provide opportunities for GHG mitigation that few other jurisdictions possess. Allocations of wood flows to long-lived or short-lived products or bioenergy had a substantial impact on BC's future emissions profile. The mitigation analysis revealed that it was better for BC to consume the harvested biomass within Canada and only export those HWPs that would be used as long-term construction materials, such as structural lumber and mass timber products. Using this approach, BC could mitigate 68% of the emissions from harvested wood products. For this strategy to be successful, BC needs to have access to the US and Chinese construction markets, or the mitigation outcomes will be constrained by the limited size of the domestic market. However, a bioeconomy strategy that relies totally on exports of long-lived timber products will have a significant impact on international trade, and could fail economically as pulp, bioenergy and other short-lived uses of wood have their exports restricted. The more practical scenario that focused on increasing wood construction market shares within Canada had a small but politically and environmentally meaningful contribution to the province's low carbon building material plan with a 3 $MtCO_2e$ $year^{-1}$ emission reduction from harvested wood products by 2030 and 4 $MtCO_2e$ $year^{-1}$ by 2050. These reductions are achieved only through increase in carbon retention in wood products, while additional emission reductions through the substitution of emissions-intensive building materials are not included here. Because a demand driven bioeconomy can have conflicts with the targeted environmental outcomes, BC may wish to adopt a hierarchical climate change mitigation incentive system that can co-exist with the other market-drivers to facilitate the achievement of optimal emission reductions. In addition to this study, which conducted mitigation analyses from a biogenic emissions perspective, the development of this system would require a comprehensive understanding of the substitution effects of wood constructions and wood-based biofuels.

3.6 Methods

This section describes the study period, the data sources, the model and the tools used in this research. It also outlines the rules for shifting wood supply used for the inward scenarios.

3.6.1 Study period

A GHG inventory report presents the carbon emissions and storage from 1990 to the year with latest data available [101]. In some analyses, the study period may date back to 1900. This study's goal was to contrast the emission consequences of various *future* bioeconomy strategies. Historical HWPs storage and emissions arise from wood products that have already been manufactured, traded and consumed. The *future* bioeconomy strategies investigated in this study are unable to influence the historical storage or emissions, except through possible changes in recycling of wood products which are addressed in Ch. 5. Also, the inherited emissions from pre-2016 harvest would be the same for all scenarios and therefore only the differences in future scenarios are addressed here. For these reasons, the year with latest available data (i.e., 2016) was chosen as the base year. This year was considered to be a suitable representative year for BC's forest products sector as the economy had recovered from the Global Financial Crisis, the wood products exports to the US had not been significantly affected by the renegotiation of North American Free Trade Agreement (NAFTA) nor the recent escalated trade tensions with China. This study therefore chose to simulate the HWPs carbon dynamics between 2016 and 2050. The latter year was chosen because it was the latest period for which most jurisdictions had defined their mitigation targets when this study was initiated. Although the carbon storage benefits of long-lived uses of wood may have been revealed in more detail if the simulation was conducted over a longer time horizon, this study did not extend the study period to hundreds of years in order to focus on the next approximately 30 years. BC's mitigation strategy was expected to shift once it enters the net negative emissions in the latter half of this century and transits to new mitigation requirements. It is therefore difficult to simulate a meaningful outcome when the study period is beyond the time horizons of current mitigation policies and targets.

3.6.2 Data sources

The projections of annual harvest rates to 2050 used in this study came from BC FLNRORD and was based on compilations of annual allowable cut (AAC) projections and the fractions of AAC that were assumed to be realized. These projections were also used by Xu et al. [42], who explored alternative forest management strategies. The scope of this study was limited to the production, trade and usage decisions along the post-harvest wood products supply chain. This study did not explore alternative forest management and timber harvest strategies and therefore the harvest projections were held constant among the nine HWPs mitigation scenarios. This study also did not explore alternative uses of bark as a feedstock for liquid biofuel fuel production and assumed that it can only be used as hog fuel, because published literature has indicated that high bark contamination in feedstocks can significantly reduce the yield of liquid biofuels [185]. Consequently, emissions from hog fuel combustion of 245 $MtCO_2e$ between 2016 and 2050 (on average 7 $MtCO_2e$ $year^{-1}$) were the same for all nine scenarios. Hog fuel emissions were not included in the scenario comparisons. Under bark data were used for carbon allocations, in accordance with the industrial roundwood data published by FAOSTAT and BC's mill report [35, 276].

The BASE scenario was a business-as-usual scenario that served as a baseline and held the biomass allocation ratios in 2016 constant until 2050. The biomass flow data involved four categories: the allocations of biomass to different processing facilities, the recovery factors of primary wood products, the quantities of international forest products subjected to trade and the partitions of wood commodities to different end-uses.

The biomass allocation data were compiled from the mill reports published by the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development (BC FLNRORD) [35] which reported the biomass flow for 2016 by process facility types (e.g., sawmill, plywood mill etc.). The mill report also estimated the average product recovery factors in BC's sawmills, that is, the percentage of biomass that was converted to lumber, wood chips, sawdust and shavings. The recovery factors of wood-based panels were acquired from Athena Sustainable Material Institute (ASMI) life cycle assessment (LCA) studies [281, 282, 324], United Nations Economic Commission for Europe (UNECE) report on forest products conversion factors [283] and the Consortium for Research on Renewable Industrial Materials (CORRIM) LCA studies [325, 326]. The recovery factors for pulp were collected from UNECE report [283]. International trade data for BC's HWPs were collected from Statistics Canada (StatCan) [327], Forestry Innovation Investment (FII) [76] and FPInnovations [94]. The end-use partitions were compiled from several Canadian Wood Council (CWC), US Department of Agriculture (USDA) etc. joint-research reports as well as derivative calculations based on these reports [81, 82, 84–90] and the Forest Economic Advisors (FEA) data center [91].

The domestic primary wood products demands for the IN_POP and IN_CONS scenarios were calculated based on population projections and the market share of timber constructions. Population observation and projection data were collected from StatCan [298]. The market share of timber constructions was compiled from Elling et al., McKeever et al. and market share report by Canadian Institute of Steel Construction [80–82].

3.6.3 HWPs carbon dynamics model, carbon retention patterns and software programs used

The HWPs carbon dynamics model developed for use in this study was the MitigAna model. The MitigAna model was implemented using the Carbon Budget Modeling Framework for Harvested Wood Products (CBMF-HWP), a modeling software developed by Canadian Forest Service (CFS) [46]. The CBMF-HWP has been used to implement several regional and national HWP models in Canada and abroad. Details about HWP C models are reviewed in Ch. 1.

The MitigAna model is a HWP mitigation analysis model developed based on BC's biomass flow structure that was compiled from the above-mentioned sources, with reference to the NFCMARS-HWP model [46], the BC-HWPv1 model [265], and some modeling principles in Brunet-Navarro et al. [249]. The resolution of the product categories in the model was designed to be as high as possible with reference to FAO's forest product categorization and definition [276], but had to make necessary compromises when data were not available. This meant that some product categories had to be combined due to the low resolution of the data. The development details of MitigAna are described in Ch. 2.

The model used a mix of Gamma distribution and first-order decay patterns for the HWPs carbon retention modeling (see Section 2.2.3.2 and 2.2.7). The landfill module was turned off for this study. Carbon sent to landfill was assumed to be instantaneously released to the atmosphere as CO_2, in accordance with the Tier 2 method outlined in the IPCC reporting guidelines [47].

3.6.4 Biomass supply reallocation rules for the inward-focused scenarios

In order to meet the domestic demand established in the inward-focused scenarios, some of the exported HWPs needed to be shifted to domestic uses. This reallocation commenced with roundwood as increasing the consumption of logs domestically was expected to provide additional carbon benefits. This was because approximately 10% of BC's roundwood harvest was exported directly as logs with China being the major importer (59% of the direct log export) and Japan being the second (23%) [308]. HWPs in China and Japan, in general, have shorter service-lives than the ones in BC [92, 274]. In addition, additional processing of wood products generally adds value to the product and reallocating logs to domestic use would likely create additional jobs and value for the province [328].

If all exported logs were reallocated to domestic manufacturing but still could not fulfill the demand of a particular product established in the scenario, the export of this products was reallocated to domestic use. For example, if the domestic market demanded more sawnwood, and all raw logs had already been consumed domestically, then exported sawnwood would be shifted to the domestic market to meet this demand. If a complete shift of the exported amount still could not adequately meet the domestic demand, then the biomass sent to the competing products[7] was reallocated to produce this specific product, provided that some criteria were met:

- the competing product had a shorter service life, and/or
- the competing product had a smaller substitution effect.

Ideally, all the biomass shifts in the mitigation analysis would be completed by the mitigation modeling software using a bottom-up design and following the shifting rules established. However, the CBMF-HWP modeling framework did not have this feature ready at the time of this research. The biomass reallocation decision made in this study were conducted using a top-down design with a binary search algorithm, the Python demand search tool (PyDS), which was external to the CBMF-HWP modeling framework.

3.6.5 Simulation steps

The workflow of the model runs for this study are described in Fig. 37.

[7] Competing products are HWPs that are manufactured from the same raw material. One product therefore competes for the biomass supply with the other. For example, MDF mills and pulp mills may compete for fibre supply from pulp logs.

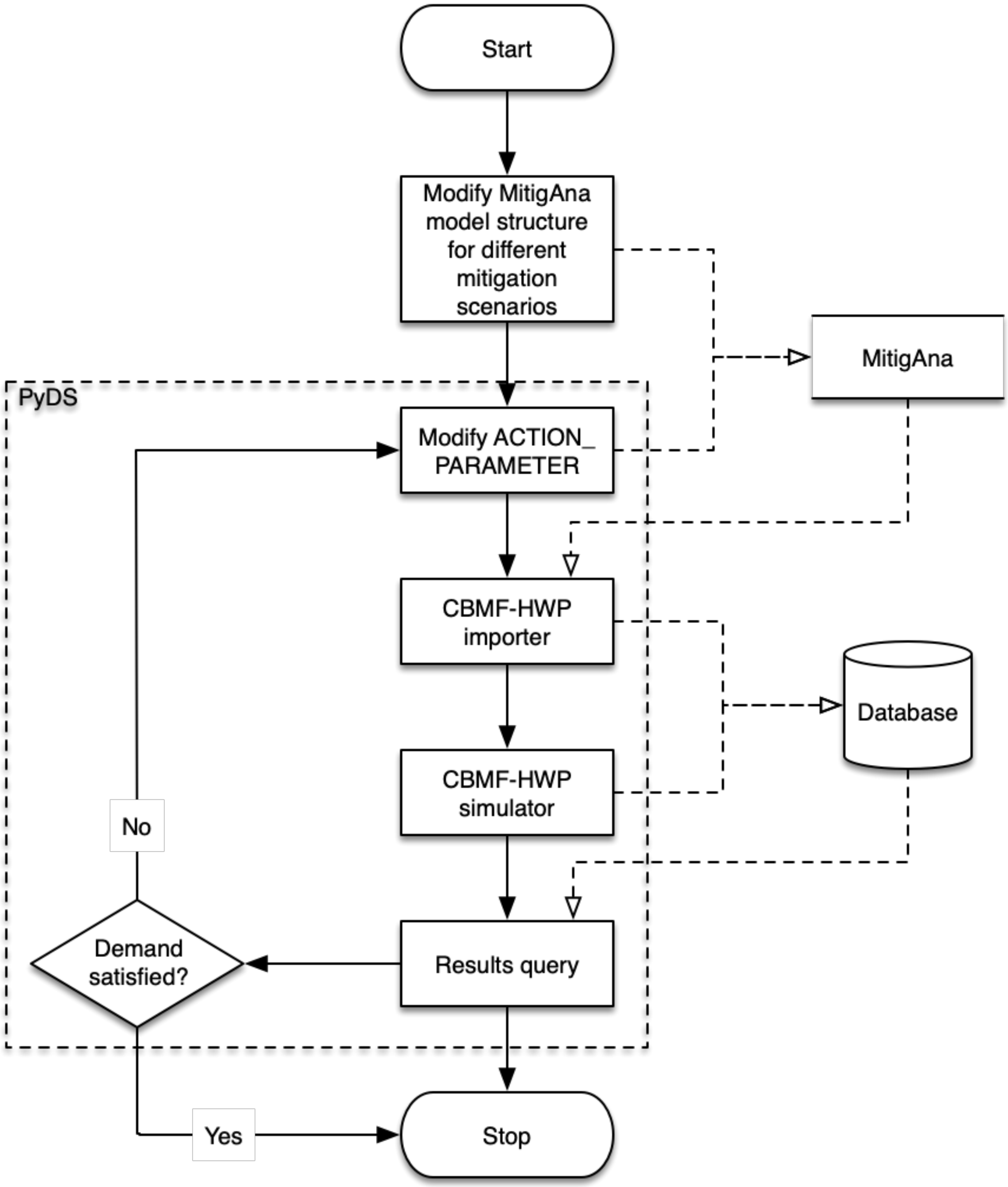

Figure 37. Flowchart of the mitigation model runs (PyDS: python demand search tool; CBMF-HWP: carbon budget modeling framework for harvested wood products; MitigAna: a harvested wood products carbon dynamics model for mitigation analysis).

The process began with modifying the MitigAna model structure for different requirements established in the mitigation scenarios. The action parameter time series (i.e., the wood allocations to the facilities, trade, and end-uses) were modified to satisfy different HWP's demands in different scenarios. Output of the CBMF-HWP simulator was queried to determine whether the domestic demand was satisfied or not (Fig. 37). If demand was not satisfied, the PyDS module would initiate a reallocation process and repeat the simulation until the demand was satisfied. The scenario results were then compiled.

3.6.6 *Mitigation Indicator*

The percentage reduction in emissions was selected as the mitigation indicator. This parameter was calculated using the percentage difference between the emissions of the BASE scenario and the emissions of the other mitigation scenarios:

$$\%\Delta = \frac{E_{BASE} - E_{SCEN}}{E_{BASE}} * 100\%$$

where $\%\Delta$ is the emission reduction in percentage difference, E_{BASE} is the emissions of the BASE scenario, and E_{SCEN} is the emissions of one of the mitigation scenarios, for example, the IN_POP scenario.

4 SUBSTITUTION BENEFITS OF BRITISH COLUMBIA'S FOREST PRODUCTS FOR GREENHOUSE GAS MITIGATION

4.1 BACKGROUND

Assessing the mitigation potential of the forest sector relies on three core principals [311],

1. quantification of the differences in net greenhouse gas (GHG) balances caused by changes in human activities, relative to a baseline;
2. estimation of emissions when and where they occur and the type of gas emitted; and
3. quantification of the changes in carbon stocks and emissions in forest ecosystems, from harvested wood products (HWPs), and from the substitution of emission-intensive products.

This chapter evaluates the substitution benefits of various potential bioeconomy strategies in the province of British Columbia (BC), Canada. The substitution benefit refers to the GHG emissions avoided by using wood or wood-based bioenergy in place of other materials and fuels. For example, solid and composite wood products can be used as structural and non-structural materials in the construction sector. These wood products generally require less energy to manufacture producing fewer GHG emissions than their steel or concrete equivalents and they store carbon that was previously removed from the atmosphere through forest growth [28, 30, 329]. Therefore, substituting wood for steel and concrete in the building sector can reduce energy consumption and process emissions. Depending on the time frame considered, the forest biomass feedstock types utilized, and the carbon intensity of the fossil fuels to be substituted, wood-based bioenergy may provide positive or negative substitution benefit [159–161]. Wood is a renewable resource that contains carbon that has been previously sequestered by the forest. The combustion of wood of any form, whether pellets or biofuel, results in an instantaneous release of the carbon contained in the wood to the atmosphere [101]. Since wood resources are renewable and the carbon emitted from wood can be re-captured by the forest, using wood-based bioenergy can reduce the use of fossil fuels and contribute to decarbonization [330]. Quantification of the substitution benefit requires a detailed assessment of the GHG emissions throughout the life cycle of wood products and their functional equivalents, including emissions during the material acquisition, production and end of life stages.

This study seeks to quantify the substitution benefits of wood as a construction material and as the feedstock for "drop-in" biofuels[8] production for several reasons. Firstly, wood used as construction material and energy are two important components in the structure of BC's economy and they are the two most important sectors in greenhouse gas emissions globally [231]. Secondly, there is limited reliable information on the substitution benefit of wood replacing other materials in sectors other than construction. Sathre and O'Connor [30] conducted a meta-analysis of 21 studies, all of which are for the construction sector. Leskinen et al. [28] reviewed 51 studies and 79% of them were related to the construction sector. Thirdly, electricity substitution may not be beneficial to reducing GHG in places where energy is produced from low-emissions or renewable sources such as BC where electricity is dominantly produced by hydro power. BC generated 268 PJ of electricity in 2016, 88% of which was from hydro [317, 331]. Other renewable sources generated another 10.4%. There is therefore little room for forest biomass to reduce GHG emissions unless it is used in a sector that is difficult to electrify, such as aviation and long-range transportation [173, 332, 333]. With woody biomass residues being available throughout the wood products supply chain in BC, they can potentially provide necessary feedstock for "drop-in" biofuel production. Fourthly, alternative substitution options such as flooring, furniture and decking have been shown to be small or even negative [110]. In terms of paper-based products, the benefit has been reported to be either negative or uncertain compared to digital media [127, 128, 131].

A commonly used measurement of the wood products' substitution effect is the displacement factor (DF) proposed by Schlamadinger and Marland [104]. It quantifies the amount of emission reduction achieved per unit of wood use and indicates the efficiency of the substitution effect. The DF was defined as the mass unit of carbon emissions avoided per mass unit of carbon contained in the additional wood used (e.g., tC emissions avoided (tC in additional wood)$^{-1}$) [30]. The mass unit of carbon in the numerator and denominator cancels out and the DF is dimensionless.

There have been several attempts to quantify DF's for wood products (e.g., [28, 30, 110]). The preferred way to calculate the displacement factor of wood replacing concrete and steel as a building material is to use the results of a comparative life cycle assessment (LCA) between functionally equivalent more and less wood intensive buildings. The LCA should include the buildings' GHG emissions from cradle to grave using the same scope and boundary conditions. The two buildings

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[8] "Drop-in" biofuels refer to renewable gasoline, diesel and jet fuel that are functionally equivalent to conventional fuels and can be "dropped into" existing infrastructure.

should be functionally equivalent and have similar square footage, location and completion year, and preferably be completed recently. However, it is usually challenging to satisfy all of these ideal conditions. For example, it has been difficult to find a concrete or steel functional alternative in Prince George that was completed around 2014 to compare to the Wood Innovation and Design Centre (WIDC). Therefore, previous LCA studies usually contrast a more wood intensive building with a hypothetical less wood intensive functional equivalent (such as [123]), or vice versa (such as [107]). Although LCA research teams can sometimes access data through internal connections, a lack of context specific data in the existing life cycle databases and tools still represents a major challenge [334]. This study selected several comparative building LCAs and calculated their displacement factors. An uncertainty analysis was then conducted to estimate the substitution benefits of wood displacing emissions-intensive materials in constructions under various forest sector mitigation strategies.

To our knowledge, no published study has calculated the displacement factor of wood-based "drop-in" biofuels. Previous publications have focused on bioenergy substitution for heat and electricity generations (e.g., [110]). "Drop-in" biofuel can be produced through oleochemical, biochemical or thermochemical means. Oleochemical pathways utilize oil feedstocks such as oilseeds and animal fats. Presently, only biochemical and thermochemical technologies can convert woody biomass to biofuels [61]. However, biochemical pathways create intermediate products that have higher commercial value than the fuel end product [181, 185]. The commercial production of drop-in biofuels therefore has substantial economic challenges [182]. Three thermochemical biofuel pathways exist: gasification, hydrothermal liquefaction (HTL) and pyrolysis [61]. Gasification utilizes sophisticated chemical engineering technologies and consequently has a high capital intensity. Very large plants need to be built in order to use economies-of-scale to offset these high capital requirements [184]. These large plants have very high biomass demands which severely constrains where they can be located. Given BC's reducing biomass harvest, gasification was not considered to be a viable option in the foreseeable future for this province. Consequently, this study calculated the displacement factors of wood-based "drop-in" biofuels converted from hydrothermal liquefaction and pyrolysis pathways based on published LCA results for BC [185, 197].

For simplicity, this study has not assumed a technological barrier for the "drop-in" biofuels, the scenarios could be applied for any 35-year period from once the technology has become available. It is noteworthy that wood-based "drop-in" biofuels are still undergoing active research and development, whereas the technology of light frame and heavy timber construction is more mature. Forest biomass feedstocks contain high level of oxygen and impurities that require extensive processing such as upgrading with hydro-treatment or more frequent turnover of catalysts [183]. Substantial cost reduction and optimization are required before wood-based transportation fuels can be commercialized [181].

Despite the evident challenges, quantifying the substitution benefit can inform evidence-based decision making to better evaluate the climate impact of wood use options in the construction and transportation sectors, and to develop more effective GHG mitigation strategies using the limited amount of harvested forest biomass in BC. Avoided emissions from substitution effects need to be added to mitigation analyses to recognize the total impact beyond the carbon storage and emission perspective. The objectives of this chapter are:

1. the estimation of the displacement factors of wood construction and wood-based “drop-in” biofuels;
2. the quantification of the substitution benefits of a wood construction- or a wood-based “drop-in” biofuel-focused bioeconomy; and
3. the development of mitigation strategies that include substitution benefits.

4.2 RESULTS

The Methods section (Sec. 4.5) is placed after the conclusions. In this Results section, relevant LCA studies were analyzed to determine the ranges of displacement factors reported for wood buildings and wood-based “drop-in” biofuels. These ranges were then analyzed to determine the distributions for quantification and uncertainty analysis of the substitution benefits under various mitigation scenarios.

4.2.1 DISPLACEMENT FACTORS

Displacement factors vary by country and across regions due to various factors including different biomass sources, energy mixes, facility locations, transportation distances and so on. This study restricted the substitution benefit calculations to BC. All the harvested biomass modeled in this study originated from BC. The harvest projections used in this study came from BC FLNRORD which is the same dataset used by Xu et al. [42]. The scope of this study was limited to the production, trade and usage decisions along the post-harvest wood products supply chain. This study did not explore alternative forest management and timber harvest strategies and therefore the harvest projections were held constant among the nine HWPs mitigation scenarios. This study also did not explore alternative uses of bark as a feedstock for liquid biofuel fuel production and assumed that it can only be used as hog fuel, for published literature has indicated that high bark contamination in feedstocks can significantly reduce the yield of liquid biofuels [185]. Consequently, emissions from hog fuel combustion of 245 $MtCO_2e$ between 2016 and 2050 (on average 7 $MtCO_2e$ $year^{-1}$) were the same for all nine scenarios. Hog fuel emissions were not included in the scenario comparisons. Under bark data were used for carbon allocations, in accordance with the industrial roundwood data published by FAOSTAT and BC's mill report [35, 276]. Interprovincial trade from BC to other Canadian provinces was considered to be domestic (inward) consumption and was not modeled as an export. The substitution benefits of BC's wood being consumed in other Canadian provinces as construction material and drop-in biofuel feedstock were calculated using the same DF's as for BC.

4.2.1.1 Construction material substitution

A comprehensive literature search of LCA studies on wood construction was conducted. Only the data in the wood construction LCA studies that met the following criteria were considered. Only whole building LCAs were included in the dataset. Therefore, studies that only focused on building components such as windows, doors, walls, poles, floors and so on were excluded. The literature search focused on mid- to high-rise buildings because a majority of the single-family houses in BC are already being built with wood, leaving very little room for additional wood use above the business-as-usual baseline. Comparative LCAs were selected to provide confidence that the displacement factor was calculated based on the same scope and boundary conditions. LCA studies that assumed electricity and heat generation from coal were excluded as BC is a hydro-dominated province. Displacement factors would be higher if the study compared structural wood products to steel and concrete produced using coal-generated energy, but this would overestimate the substitution benefit for BC.

The displacement factor calculation in this study only included embodied emissions and excluded operational emissions. A building's operational energy consumption over the lifetime is in general more significant than its embodied energy [335]. Concrete buildings are usually portrayed as having lower operational energy than wooden buildings due to their higher thermal mass [336]. However, as the building sector responds to society's increased focus on energy efficiency and deep decarbonization, the embodied emissions become more significant and they are able to provide immediate climate benefits through substitution [116]. Building LCAs that included operational emissions rely on the accuracy of the LCA databases and tools because the operational emissions over the building's lifetime are estimated based on building's service life, maintenance, renovation and energy consumption assumptions that will occur in the future. Tall and heavy timber constructions are relatively recent development, and consequently there is a lack of information about operational emissions compared to the embodied emissions for these building types. For this reason, it is common for comparative building LCAs to either assume that buildings would meet the same insulation requirement and have the same operational emissions (e.g., [123]), or simply exclude operational energy from the scope of the study (e.g., [337]).

The calculated displacement factors of wood products replacing steel and concrete as construction materials based on the selected building LCA candidates are summarized in Tbl. 6.

Table 6. The displacement factors of wood products replacing steel and concrete as construction materials by building type, material replaced, and jurisdiction.

Type	Building material	Jurisdiction	Completion year	Comparison	DF	Reference
Residential building	Heavy timber vs. concrete	British Columbia	2017 vs. 2016	Actual buildings	1.03	[157, 313, 337]
		United Kingdom	2009	Actual vs. hypothetical	0.35	[338]
		Sweden	2008	Actual vs. hypothetical	0.44	[338]
	Light weight wood frame vs. concrete	Australia	2014 vs. 2015	Actual buildings	0.98	[115]
		United States	2004	Hypothetical buildings	1.90	[339]
		Sweden and Finland	1994	Actual vs. hypothetical	2.40	[248]
Non-residential building	Heavy timber vs. concrete	British Columbia	2014	Actual vs. hypothetical	1.22	[123]
	Light weight wood frame vs. steel	New Zealand	2010	Actual vs. hypothetical	1.11	[124]

The calculated displacement factors displayed a wide range from 0.35 to 2.4 (Tbl. 6). This was expected as construction types, building year, building codes, transportation distance, energy mix of different jurisdictions, and whether the study used actual buildings or accounted operational energy can all have significant impacts on the results. The range in Tbl. 6 generally agrees with previously published literature reviews [28, 30, 110]. There did not appear to be a substantial difference between wood substitution for reinforced concrete or wood substitution for steel based on the LCA data that were available to this research ([124] in Tbl. 6) and therefore for the remainder of this chapter, these two building materials are discussed collectively.

Provided that other factors remain the same, light weight wood frame, in theory, should have a higher displacement factor than heavy timber construction because less wood mass is needed to replace the same amount of concrete (or steel). The calculated displacement factors of residential buildings in Tbl. 6 generally followed this assertion. The displacement factors of non-residential buildings did not follow this assertion, probably because of the small sample size and the other factors such as wood source, building design and transportation distance. Non-residential buildings can be functionality-driven with large variability. For example, a theater, shopping mall, school and gym can have very different designs and floor spaces.

4.2.1.2 Transportation fuel substitution

Facility location, energy mix, transportation distance and forest biomass availability are important factors for the environmental impact of wood-based "drop-in" biofuel. For this reason, only LCA studies that analyzed biofuel production facilities based in Canada (with an emphasis on BC) were selected for these displacement factor calculations. The calculated displacement factors of wood-based "drop-in" biofuels are summarized in Tbl. 7.

Table 7. The displacement factors of wood-based "drop-in" biofuels by fuel type, pathway, and facility location.

Fuel Type	Pathway	Facility location	Displacement factor
Jet fuel	Pyrolysis	Vancouver	0.40[pc]
		Vancouver Island	0.40[pc]
		Prince George	0.38[p]
	HTL	Wood pellets central integrated refinery	0.40[hc]
		Forest residue central integrated refinery	0.47[hc]
		Bio-oil distributed refinery	0.49[hc]
Diesel	Pyrolysis	Vancouver	0.43[pc]
		Vancouver Island	0.43[pc]
		Prince George	0.42[pc]
		Ensyn Ontario Facility, by rail to California	0.46[oc]
		Ensyn Ontario Facility, by truck to California	0.42[oc]
	HTL	Wood pellets central integrated refinery	0.43[hc]
		Forest residue central integrated refinery	0.50[hc]
		Bio-oil distributed refinery	0.52[hc]
Gasoline	Pyrolysis	Vancouver	0.43[pc]
		Vancouver Island	0.43[pc]
		Prince George	0.42[pc]
		Ensyn Ontario Facility, by rail to California	0.46[oc]
		Ensyn Ontario Facility, by truck to California	0.43[oc]
	HTL	Wood pellets central integrated refinery	0.43[hc]
		Forest residue central integrated refinery	0.50[hc]
		Bio-oil distributed refinery	0.52[hc]

[p] These displacement factors were calculated based on fuel yield and LCA results in [185]. Physical conversion factors from [318] [193].
[h] These displacement factors were calculated based on fuel yield and LCA results in [197]. Physical conversion factors from [340] [341] [193].
[o] These displacement factors were calculated based on carbon intensity reported by [180].
[c] Global warming potentials of conventional fuels were obtained from [209] [208] [210] [211].

Despite the range of fuel types, pathways and facility scenarios considered, the range of displacement factors in Tbl. 7 was relatively narrow, ranging from 0.38 to 0.52 with an average of 0.45 and a standard deviation of 0.04.

4.2.1.3 Displacement factor distributions used for substitution benefits uncertainty analysis

A triangular distribution was used to describe the uncertainty of the DF's. This type of distribution was chosen because it uses the three-point estimation technique (i.e., best-case, most likely and worst case estimates) to construct a probability distribution for uncertainty analysis based on limited quantitative information.

For the DF distribution for wood constructions, the lower limit was set to 0.35, the mode was 1.03 and the upper limit was 1.22 (Fig. 38 (a)). The value of 1.03 calculated from Bowick [157, 313, 337] was chosen as the mode and the two highest values in Tbl. 6 (i.e., 1.90 and 2.40) that were calculated based on structures built over a decade ago (i.e., 2004 and 1994, respectively [248, 339]) were excluded from the distribution. The value of 1.03 in Tbl. 6 was selected as the most-likely value because it was calculated from comparable LCA studies of *recently completed*, *actual*, *heavy timber* and reinforced concrete buildings [157, 313]. Comparing an *actual* building with a *hypothetical* one is common in LCA studies because of the difficulty in finding structures that are functionally equivalent. However, the assessment of a hypothetical building relies on the thoroughness of the assumed building design and the accuracy of the LCA databases and tools, which contribute to higher uncertainties compared to the assessment of an actual building. The LCA comparisons for actual buildings in Tbl. 6, therefore, were considered to provide more confident displacement factors for wood buildings (i.e., [313] and [115] in Tbl. 6). When developing the distribution (Fig. 38 (c)), more weight was given to the heavy timber buildings with lower values, because of their market growth opportunities. Lightweight wood-frame residential construction has a relatively mature market [80–82, 134] and little market growth potential is remaining, whereas the market for heavy tall timber residential buildings and non-residential buildings has substantial future growth potential. In addition, due to increased climate awareness and updated building codes influencing the material content of buildings, and the concrete building sector focusing on reducing their carbon footprint [342], the DF will likely decrease with time. Therefore, the distribution is left skewed to provide a measure of future proofing.

For the DF distribution of wood-based "drop-in" biofuels, the lower limit was set to 0.38, the mode was 0.45 and the upper limit was 0.52 (Fig. 38 (b)). Unlike the DF for buildings, the displacement factors of renewable transportation fuels in Tbl. 7 are within a narrow range. Therefore, this study selected the average value of 0.45 as the mode. The upper limit was the highest value and lower limit was the lowest value in Tbl. 7.

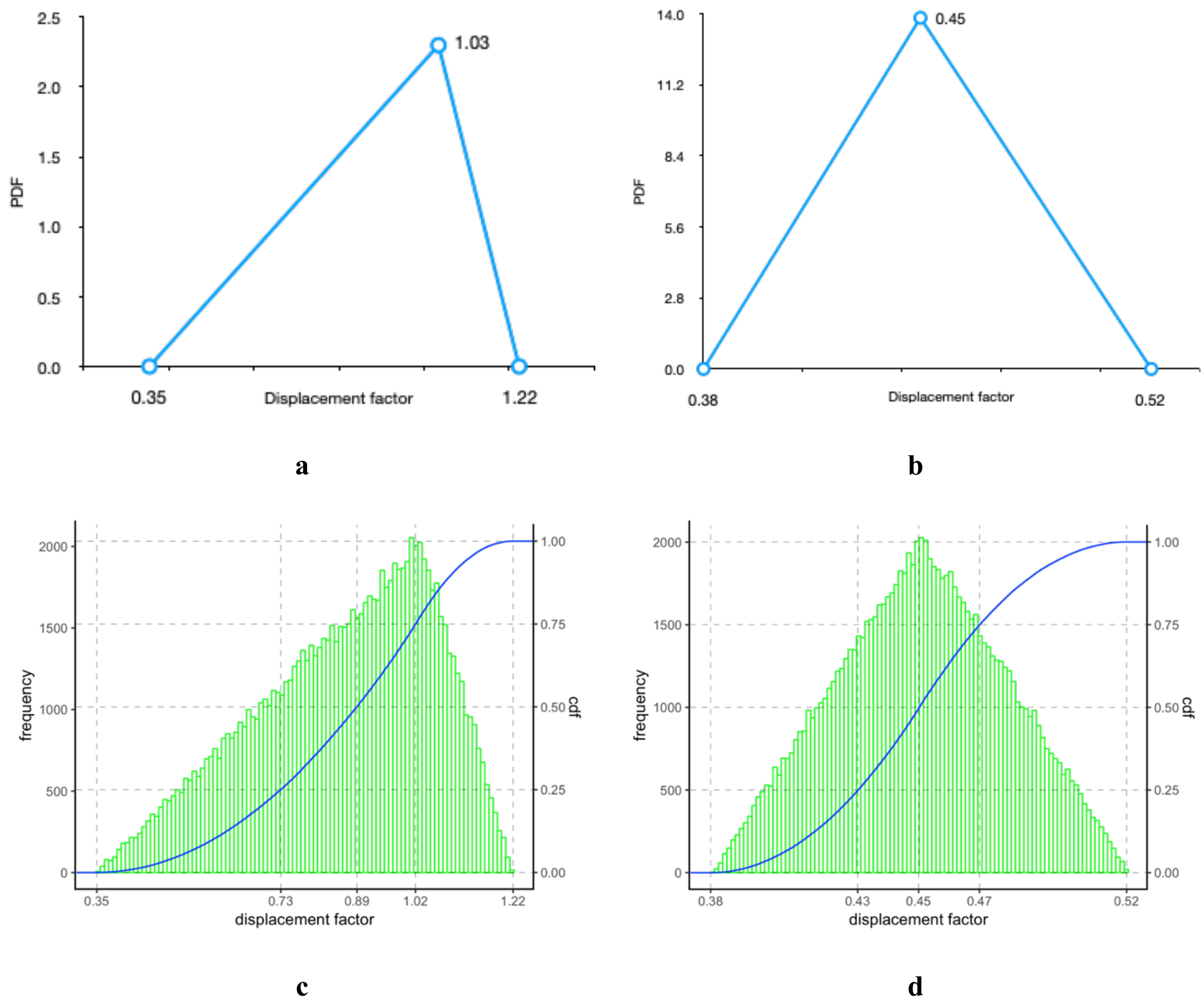

Figure 38. Displacement factor distributions of domestic wood constructions and wood-based “drop-in” biofuels. a — the determined triangular probability density function (pdf) of displacement factors of wood products replacing steel and concrete as construction materials in the domestic market, b — the determined triangular probability density function (pdf) of displacement factors of domestic wood-based “drop-in” biofuels replacing conventional fossil-based fuels, c — frequency and cumulative density diagram (cdf) of the 100,000 sample draws of displacement factors from (a), d — frequency and cdf of the 100,000 sample draws of displacement factors from (b).

4.2.2 *AVOIDED EMISSIONS DUE TO SUBSTITUTION*

The actual GHG benefit that accrues from substituting wood for another material or fuel depends upon the attributes of the material or fuel that is substituted. This section first distinguishes the actions that can be regarded as contributing a substitution benefit and the actions that do not, then quantifies the avoided emissions with uncertainty intervals of various scenarios calculated based on this rule and the DF distributions.

4.2.2.1 What counts towards substitution benefit?

BC harvested about 66 million m^3 of logs that contained roughly 60 $MtCO_2e$ in 2016 [35]. Timber construction has a share of over half of the total residential construction market in BC and US, and roughly a quarter for the rest of Canada [80–82, 134]. One extreme scenario is to assume that all BC's harvested biomass is manufactured (with losses in manufacturing and process energy use) into wood products that are used in the construction sector. However, in this context, it is important to consider whether all of these wood products would be used to displace concrete or steel constructions.

Not all forest biomass used for construction or bioenergy meets the eligibility criteria for substitution benefit [112–114]. Some buildings may be predetermined by the market to be constructed with wood, and steel or concrete has never been considered as an alternative. The eligibility criteria for substitution benefit can be illustrated with an example. If timber construction has a 50% market share, without other incentives, when 100 new buildings are constructed, 50 of them will be built with wood and the other 50 of them with other materials, although in BC it predominantly would be reinforced concrete. In this case, there is no wood-to-other-material substitution.

If there is an incentive by the government encouraging the use of wood in the construction sector, for example with a subsidy, regulations of embodied energy, or changes in building codes, then the wood construction market share may increase, for example from 50% to 60%, and consequently shifting 10 buildings that would have been constructed with concrete to be constructed with wood. In this case, wood in these 10 buildings can be regarded as wood-replacing-concrete and counted towards substitution benefit.

It can be then generalized that a substitution effect is valid only when there is a change, such as policy or human behavior, that causes the buildings that would otherwise have been constructed with steel and concrete to be now built with wood.

In the Ch. 3, several scenarios were created to evaluation the carbon storage and emission of different woody biomass trade and utilization options. These scenarios are presented below:

- BASE scenario

  This is the business-as-usual baseline scenario. This scenario was based on the 2016 market partitions and production efficiencies of wood products and assumed that the partitions and efficiencies remained constant from 2016 to 2050.

- ALL_CONS scenario

  This is the first of two theoretical extreme scenarios. This scenario assumed that all of BC's harvested biomass was manufactured into construction materials. Consequently, all sawlogs were sent to sawmills or plywood mills. Pulp logs were sent to oriented strand board (OSB) mills. Milling residues such as wood chips and sawdust were sent to medium density fiberboard (MDF) mills and particleboard mills. Sawnwood, plywood, OSB were assumed to be used for structural construction or repair and remodeling. MDF and particleboard was assumed to be used to build non-structural components, such as kitchen cabinets, kitchen and bathroom counters, doors and moulding.

- ALL_FUEL scenario

  This is the second theoretical extreme scenario. This scenario assumed that all harvested biomass was used as feedstock to produce renewable jet fuel, diesel and gasoline. As the carbon in wood-based fuels is conventionally treated to be instantaneously oxidized, the mitigation benefit therefore arises only from the substitution effect, i.e., avoiding emission by replacing fossil-based fuels.

- IN_POP scenario

  This is an inward-focused scenario which explored the mitigation potentials of the domestic market. This scenario assumed that the domestic HWPs demand increases in proportion to population growth rate. However, the market shares of wood products in various sectors remains the same.

- IN_CONS scenario

  This is an inward-focused scenario which explored the mitigation potentials of the domestic market. This scenario assumed the domestic demand of residential dwellings and non-residential buildings to be aligned with household growth over the study period, and the timber construction market share to be doubled in the domestic market (i.e., the timber construction market shares of residential dwellings and non-residential buildings are roughly 100% and 50% for BC respectively, and 60% and 20% for the rest of Canada).

- IN_FUEL scenario
  This is also an inward-focused scenario. This scenario assumed that all pulp logs and milling residues were sent to bioenergy feedstock to produce renewable jet fuels, diesel and gasoline while sawnwood and plywood production and market partition remained unchanged.

- OU_CONS scenario
  This is an outward-focused scenario which explored the mitigation potentials of the international markets. This scenario assumed that the HWPs remaining after fulfilling the domestic demand were exported and used as construction materials. Sawnwood, plywood and OSB produced from sawlogs or pulp logs were mainly used as a structural material. The milling residues were burnt onsite to provide energy, or manufactured into MDF and particleboards for non-structural applications such as cabinets, kitchen and bathroom counters, doors and mouldings.

- OU_CN scenario
  This is another outward-focused scenario. This scenario assumed that the HWPs remaining after fulfilling the domestic demand were exported to China and there was no utilization change in China. This assumption resulted in a majority of the exported wood products being used for short-lived purposes.

- OU_EU scenario
  This is also an outward-focused scenario. This scenario assumed that forest biomass remaining after fulfilling the domestic demand was manufactured into wood pellets and exported to EU countries. This assumption involved sending the remaining sawlogs, pulp logs and milling residues to pellet mills.

The BASE, IN_POP and OU_CN scenarios assumed that no market share changes occurred in the construction or bioenergy sectors, so these three scenarios did not have any substitutions (Tbl. 5). The substitution benefit of OU_CONS and OU_EU were excluded for three reasons.

Firstly, it is uncertain how much of these exported wood products will contribute to substitution. Taking the OU_CONS scenario as an example. In this scenario, more BC wood is used in the US and other countries for construction purposes. However, this could simply be BC wood replacing US wood or wood harvested from other countries. It cannot be guaranteed that this increased consumption is caused by increased timber construction market share.

Secondly, according to the UNFCCC, a Party is required to account for emissions from HWPs that originated from its forests, and imports should not be accounted for (i.e., the Production Approach) [47, 48]. The industrial processes and product use (IPPU) sector also accounts emissions using a production-based approach [101]. However, emissions from the energy sector are accounted for differently using a consumption-based approach in which the energy emissions within the Parties' jurisdictional boundary should be reported but not exports (i.e., the Sectoral Approach) [101]. Due to this discrepancy in accounting approaches, the beneficiaries of emission reduction depend on the origin and destination of the materials or fuels. For example, if wood pellets produced in BC were used to substitute coal for electricity generation in the United Kingdom (UK) (assuming that the coal being substituted is not consumed elsewhere in UK), then the substitution beneficiary would be UK, because UK's energy sector would achieve an emission reduction from combusting pellets in place of coal. However, the downstream emissions arising from burning these wood pellets in UK and the upstream emissions associated with producing these wood pellets in BC would all be accounted as emissions in BC's AFOLU and IPPU sectors. On the other hand, the use of HWPs for structural purposes rather than pellets for combustion are treated differently. For example, consider CLTs produced in BC, exported to the US and used to substitute for a functionally equivalent amount of steel imported from China. Assuming that this amount of steel was not produced, then China would achieve an emission reduction in its IPPU sector (i.e., a substitution benefit); BC would achieve a foreign storage benefit in the AFOLU sector; the US *may* benefit from reduced energy emissions associated with material transportation (as BC is closer to the US than China) and erecting the structure (due to the prefabricated nature of CLTs and its rapid construction process). In the two simplified examples presented above, the reduced consumption of coal and the reduced production of steel due to substitution effects have been assumed. In reality, such reduction may not be guaranteed without international cooperation on mitigating climate change. In addition, BC as a major HWPs exporter, if its HWPs are used by another jurisdiction to substitute fuels, the substitution benefit will unlikely be recognized on BC's provincial inventory report. On the contrary, manufacturing or burning these HWPs generates emissions that need to be reported by BC.

Thirdly, the displacement factors and associated ranges determined in this study are mainly for wood construction and wood-based transportation fuel that are used in BC. The displacement factors can vary significantly for foreign countries due to, for example, different transportation distances, energy mixes and building standards. For these reasons, this study only estimated the substitution benefits of the ALL_CONS, ALL_FUEL, IN_CONS and IN_FUEL scenarios.

Tbl. 8 summarizes the scenarios and whether substitution benefits were estimated in this study.

Table 8. Mitigation scenarios used in this study.

Mitigation scenarios	Abbreviation	Substitution benefit included?
1. Business-as-usual baseline scenario	BASE	N
2. Extreme scenarios		
2.1 All harvested biomass manufactured to construction material	ALL_CONS	Y
2.2 All harvested biomass as feedstock for renewable fuel	ALL_FUEL	Y
3. Inward-focused scenarios		
3.1 Domestic demand increase driven by population	IN_POP	N
3.2 Increase domestic market share of timber construction	IN_CONS	Y
3.3 Prioritize renewable fuel feedstock	IN_FUEL	Y
4. Outward-focused scenarios		
4.1 Prioritize export to US and other markets for constructions	OU_CONS	N
4.2 Prioritize export to China	OU_CN	N
4.3 Prioritize export to EU for energy	OU_EU	N

4.2.2.2 Uncertainty range of avoided emissions

The substitution benefits of the above mentioned four mitigation scenarios and the associated uncertainty analysis results are summarized in Fig. 39.

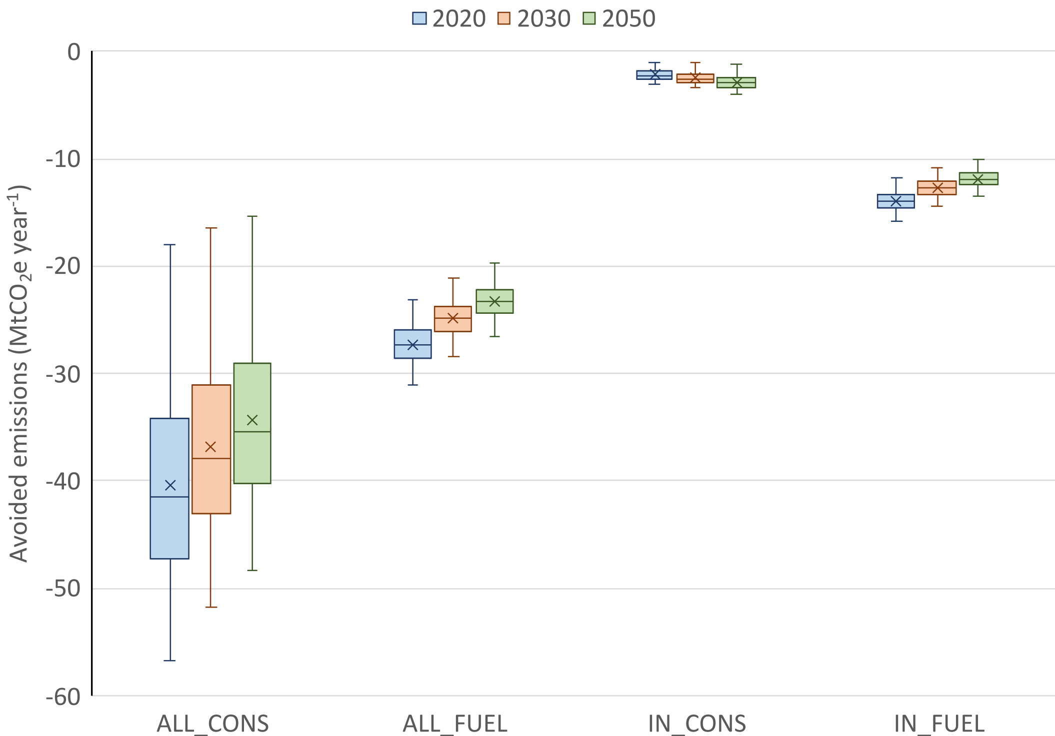

Figure 39. Box plots of annual emissions avoided in 2020, 2030, 2050 under the ALL_CONS, ALL FUEL, IN_CONS and IN_FUEL scenarios (lower value means better). Box: 1st and 3rd quartile; whiskers: maximum and minimum value; middle line: median; x: mean; no outliers.

The negative values of the y-axis in Fig. 39 indicate the amount of annual emissions that can be avoided through the substitution effect. Compared to the other scenarios, the ALL_CONS scenario avoided more emissions but also had wider uncertainties, ranging from -56.7 $MtCO_2e$ year^{-1} (max) to -18.0 $MtCO_2e$ year^{-1} (min) with a median of -37.9 $MtCO_2e$ year^{-1} and a mean of -36.8 $MtCO_2e$ year^{-1} in 2030. The median indicates larger avoided emissions than the mean because the determined displacement factor distribution is left skewed (Fig. 38 (a) and Fig. 38 (c)). The ALL_FUEL scenario ranked second with 24.9 $MtCO_2e$ year^{-1} emissions avoided as both the median and mean in 2030. The IN_FUEL scenario avoided more emissions than the IN_CONS scenario, with 12.7 $MtCO_2e$ emissions avoided in 2030 by the IN_FUEL scenario compared to the 2.5 $MtCO_2e$ avoided by the IN_CONS scenario.

Two factors contributed to the magnitudes of avoided emissions and their uncertainties, as indicated by Eq. 7 in the Methods section. The first factor is the displacement factors utilized (Tbl. 6 and Tbl. 7). The displacement factors for wood buildings are larger but more uncertain than the ones for wood-based transportation fuels. Therefore, the estimates of substitution benefits for the ALL_CONS scenario are larger but the spread of the boxes and whiskers are wider than the ones of the ALL_FUEL scenario (Fig. 39).

The second factor is the amount of wood involved in the substitution. Since all the HWPs were used for construction purposes in the ALL_CONS scenario, the amount of wood that may be counted as being available for substitution was substantial at approximately 42 $MtCO_2e$ $year^{-1}$. In contrast, even though the IN_CONS scenario assumed a boost in the wood demand in the domestic construction sector, the market itself was still relatively small and the amount of wood that can be counted as being available for substitution was only approximately 2.9 $MtCO_2e$ $year^{-1}$. Therefore, although the avoided emissions under the IN_CONS scenario were calculated using the same displacement factor range as the ALL_CONS scenario, both the benefit of the IN_CONS and its uncertainty were smaller than those of the ALL_CONS scenario. The same reason also applies to the benefits and the uncertainty ranges of ALL_FUEL and IN_FUEL scenarios.

As for the magnitude of avoided emissions over time, the ALL_CONS, ALL_FUEL and IN_FUEL scenarios are declining but for the IN_CONS scenario, they are increasing (Fig. 39). In this study, the theoretical extreme scenarios (i.e., ALL_CONS and ALL_FUEL) did not consider market constraints. For inward-focused scenarios (such as IN_FUEL), it has been established in Ch. 3 that the domestic transportation sector has the potential demand to consume all BC's forest biomass for renewable transportation fuels. Therefore, in the ALL_CONS, ALL_FUEL and IN_FUEL scenarios, the constraint was the available amount of biomass, i.e., the amount of harvest. The substitution benefit was declining for ALL_CONS, ALL_FUEL and IN_FUEL over the study period because the harvest in BC was projected to decline over the next decades. This was different for the IN_CONS scenario. The constraint for this scenario was the domestic market size. Because the domestic construction market demand was set to be aligned with the household growth which was projected to increase over the study period, the amount of wood used to substitute other materials in the construction sector also increased. Consequently, the magnitude of avoided emissions in the IN_CONS scenario increased over time (Fig. 39).

4.2.2.3 An emission profiles comparison with substitution benefits included

The substitution benefits were included in the comparison of GHG emission consequences of all mitigation scenarios listed in Tbl. 8. Fig. 40 presents the emission compositions of various HWP usage categories and the avoided emissions due to wood construction or wood-based transportation fuel's substitution effect. This figure puts the magnitude of substitution benefits into the emission context.

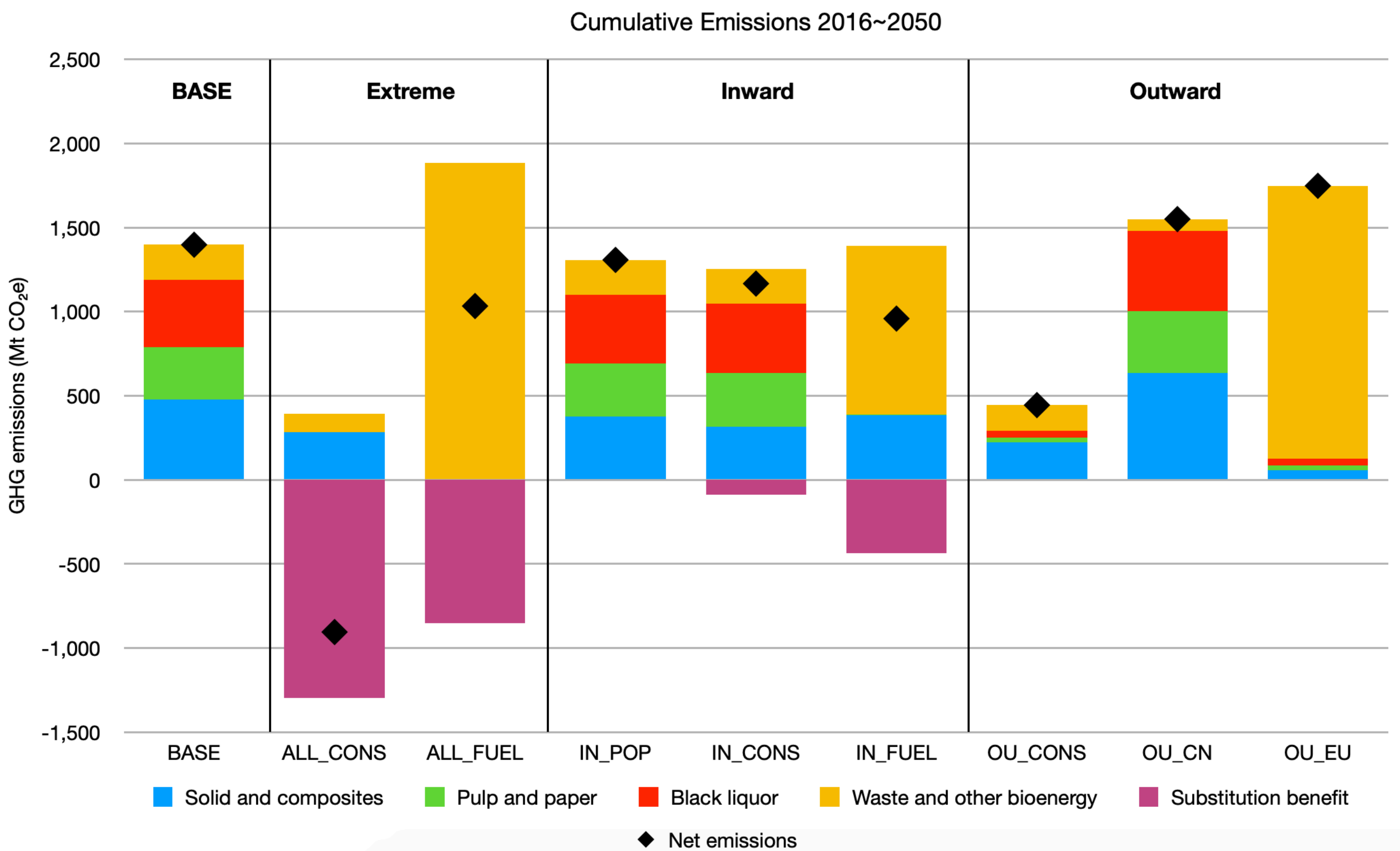

Figure 40. A comparison of the cumulative emission consequences from 2016 to 2050 of all mitigation scenarios (positive bars indicate emissions from HWPs and negative bars indicate avoided emissions in the other sectors. Lower value means better). The avoided emissions results at 50th percentile in Fig. 39 were used to represent the substitution benefits in this figure.

In the BASE scenario, the cumulative emissions from HWPs from 2016 to 2050 were 1.4 $GtCO_2e$. For comparison, BC's cumulative harvest from 2016 to 2050 was projected to be approximately 1.9 $GtCO_2e$, which was also the cumulative emissions of the ALL_FUEL scenario as all harvest was turned into transportation biofuels and assumed to be emitted in the same year of harvest (i.e., the yellow bar of the ALL_FUEL scenario). Therefore, the difference between the emissions of the ALL_FUEL scenario and the emissions of another scenario in Fig. 40 would be the HWP carbon storage of that scenario. For example, the BASE scenario had a cumulative carbon storage of 0.5 $GtCO_2e$. The ALL_CONS scenario had a cumulative carbon storage of 1.5 GCO_2e all of which was stored in wood structures. Approximately 88% of these wood structures were valid substitutions based on the assumptions made for this scenario and these substitutions avoided emissions of 1.3 $GtCO_2e$ (i.e., pink bar of the ALL_CONS scenario). Compared to the BASE scenario, the ALL_CONS scenario achieved a cumulative emissions reduction of 1.0 $GtCO_2e$. The total mitigation benefit, that is, the emission reduced and the emission avoided (compared to the BASE scenario), of the ALL_CONS scenario was 2.3 $GtCO_2e$ or 66 $MtCO_2e$ $year^{-1}$. For comparison, BC's GHG emissions in 2016 from all sectors excluding forest management were reported to be 62 $MtCO_2e$ $year^{-1}$ [10]. The mitigation benefit of the IN_CONS scenario was achieved through the same fashion except the magnitude was substantially lower. By shifting from short-lived biomass uses to wood constructions, the cumulative carbon storage of the IN_CONS scenario increased by 143 $MtCO_2e$ compared to the baseline (on average, 4.09 $MtCO_2e$ $year^{-1}$). Approximately half of the shift generated substitution benefit as the IN_CONS scenario assumed a doubling of the wood construction market share, which resulted in avoided emissions of 88 $MtCO_2e$ (about 7% of the substitution benefit of the ALL_CONS scenario). The total net mitigation benefit of the IN_CONS scenario was 231 $MtCO_2e$. For comparison, this scenario cumulatively emitted 411 $MtCO_2e$ from black liquor and 143 $MtCO_2e$ from wood pellets, both of which were used to generate energy.

In the ALL_FUEL scenario, all harvested biomass was used to produce transportation fuels and to replace fossil fuels through which the substitution cumulatively avoided emissions from fossil fuel production and consumption of 851 $MtCO_2e$. However, this scenario had no HWP carbon storage and increased the emissions from HWP by 486 $MtCO_2e$ compared to the baseline. On the other hand, the IN_FUEL scenario that converted all current short-lived uses of biomass into transportation fuel production achieved an emission reduction of 4.7 $MtCO_2e$ compared to the baseline and in addition, avoided 434 $MtCO_2e$ through fuel substitution (about 50% of the substitution benefit of the ALL_FUEL scenario). The mitigation benefits are summarized in Tbl. 9 using the scenario results minus results of the BASE scenario (Eqns. 7-9 in the Methods section).

Table 9. The mitigation benefits by scenarios from BC's perspective (in $MtCO_2e$, higher value means better). The table was sorted by total mitigation benefit in descending order.

Scenario	Storage benefit	Substitution benefit		Total mitigation benefit	
		Median	Range	Median	Range
ALL_CONS	1007	1296	561~1769	2303	1568~2776
OU_CONS	953	-	-	953	-
IN_FUEL	4.7	434	368~496	439	373~501
ALL_FUEL	-486	851	722~971	365	236~485
IN_CONS	143	88	38~121	231	181~264
IN_POP	90	-	-	90	-
OU_CN	-152	-	-	-152	-
OU_EU	-350	-	-	-350	-

Fig. 41 presents the net cumulative emissions by scenarios using Eq. 10 (see Methods section). The results of ALL_CONS, ALL_FUEL, IN_CONS and IN_FUEL are presented as uncertainty intervals because the uncertainty of their avoided emissions, as shown in Fig. 39.

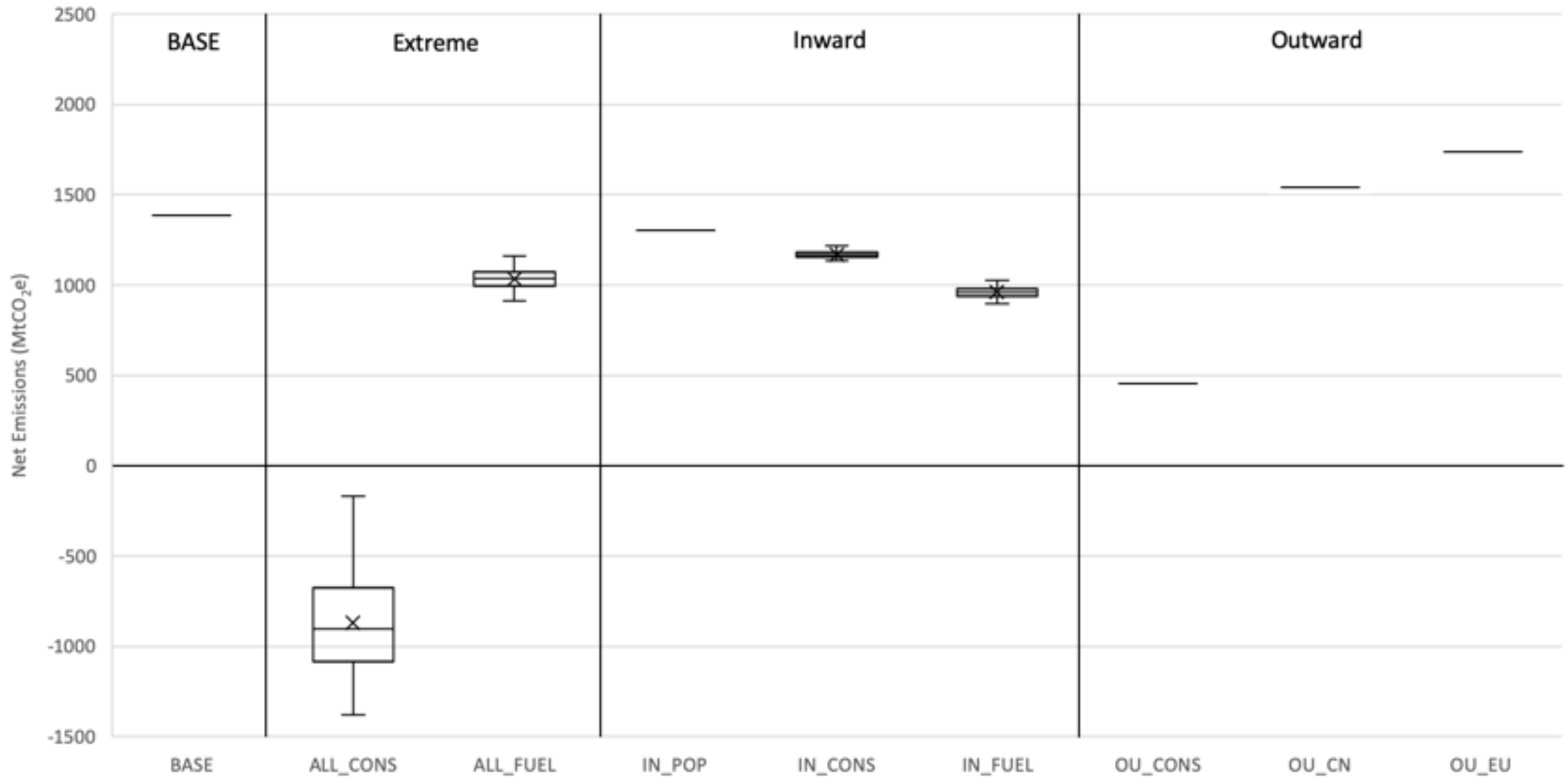

Figure 41. Box plots of the net cumulative emissions from 2016 to 2050 of all mitigation scenarios (lower value means better).

The difference in mitigation of construction and biofuel becomes more significant when the storage benefits are included. Fig. 41 and Tbl. 9 demonstrated that when the storage benefits were included, the difference in total mitigation benefits between the ALL_CONS and ALL_FUEL scenarios was substantial at approximately 1,938 $MtCO_2e$ even though their substitution benefits alone were close as observed in Fig. 39 and Tbl. 9. The BASE, IN_POP and outward scenarios have no substitution shown in Fig. 41. However, even without considering the substitution benefit which occurs outside of BC, the OU_CONS scenario resulted in the second largest mitigation benefit of 953 $MtCO_2e$ because of increased C storage in HWPs. It is noteworthy that the uncertainty range of the ALL_CONS scenario was wider than the ALL_FUEL scenario but the uncertainty range of IN_CONS scenario was narrower than the IN_FUEL scenario. This observation is consistent with Fig. 39 as the magnitude of the substitution benefit was determined by both the DF and the amount of wood that could be counted as being available for substitution (see Eq. 7 in the Methods section). There was no market constraint in place for the ALL_CONS and ALL_FUEL scenarios, therefore the wider uncertainty range of the construction DF determined ALL_CONS scenario's wider uncertainty range of the mitigation benefit. However, the inward market size for wood-based transportation fuel in the IN_FUEL scenario was larger than that for wood construction in the IN_CONS scenario, which counteracted the width of the DF uncertainty ranges and resulted in the uncertainty range of the IN_FUEL scenario to be wider than the IN_CONS scenario.

The IN_FUEL scenario ranked the third best from a GHG mitigation perspective in Tbl. 9 with a total mitigation benefit of approximately 439 MCO_2e, which was about 2 and 6 $MtCO_2e\ year^{-1}$ greater than the ALL_FUEL and IN_CONS scenarios, respectively. The IN_FUEL scenario attained higher GHG mitigation benefit than the IN_CONS scenario because, as mentioned earlier, the IN_CONS scenario was constrained by the small domestic market. The IN_FUEL scenario attained higher GHG mitigation benefit than the ALL_FUEL scenario because it fulfilled the domestic demand for wood products prior to allocating wood to transportation biofuel production. Therefore, more longer-lived wood products destined for the construction sector, resulting in increased carbon storage, were produced in the IN_FUEL option. In contrast, the ALL_FUEL option did not allocate any biomass to construction end-uses.

4.2.3 Threshold Service Life

Fig. 41 and Tbl. 9 have indicated that the mitigation benefit of the IN_FUEL scenario is larger than those of the OU_CONS and OU_EU scenarios, but smaller than that of the OU_CONS scenario (based on the assumption that the outward-focused scenarios do not provide substitution benefit to BC). Because displacing fossil fuels in domestic transportation with wood-based "drop-in" biofuels can create substitution benefit to BC, this raises the question that for the same amount of wood, whether there exists a threshold average service life for the exported wood products such that the net emissions (i.e., emissions minus substitution benefit) from the domestic wood-based biofuel equal the emissions from exported wood products. If the average service life of the exported products is lower than the threshold, BC would be better off (from the perspective of the reported GHG balance) using that biomass for wood-based drop-in biofuel production and mandating that these biofuels displace fossil fuels. For example, in the OU_CN and OU_EU scenarios, the mass-based average service life of exported HWPs in China is 5.7 years and in the EU is 0 years. Using the MitigAna model (see Ch. 2), the threshold service life was estimated to be approximately 32 years. However, this value only applies to the inward and outward scenarios in this study and would change depending on the magnitude of the exported HWPs, the amount of valid substitution and the length of the study period.

4.3 DISCUSSION

Strategically, construction is the best application of wood products from a climate mitigation viewpoint because it stores carbon that was removed from the atmosphere and reduces the emissions from other sectors. As shown in Tbl. 9, drop-in biofuels would only contribute substitution benefit, but construction has about an equal contribution from storage and substitution benefits. The randomly sampled values in Fig. 38 c and d demonstrated that 98% of the cases in which wood buildings displace concrete buildings provide a higher substitution benefit than wood-based transportation fuels replacing fossil fuels per unit of wood use (i.e., larger DF values). However, it is worth noting that technology is evolving and this will likely increase or decrease the DF values in the future. The ALL_CONS scenario in Tbl. 9 has indicated the largest theoretical substitution benefit of approximately 37 $MtCO_2e$ $year^{-1}$ that BC can achieve through the use of HWPs. However, the domestic market is too small to consume all the harvested biomass for construction purposes (see Ch. 3).

The interval of the DF distributions of wood-based drop-in biofuels was substantially narrower than and within the DF range of wooden buildings (Fig. 38). Only in few extreme cases (2% of the circumstances), the DFs of wood-based drop-in biofuels were higher than the DFs of the wood buildings. However, the IN_CONS and IN_FUEL scenario in Fig. 41 have demonstrated the importance of the market size that, if the biofuel displacement market is large enough, the substitution benefit of biofuel may outweigh the combined storage and substitution benefit of construction (Tbl. 9). The renewable fuel produced in the IN_FUEL scenario can supply half of the energy demand of BC's transportation sector or 7% of the demand of Canada's transportation sector (see Ch. 3 and Appendix C). This observation indicates that wood-based transportation fuels may have a promising potential in helping achieve the emission reduction goals set by BC, provided that the construction market is saturated and the "drop-in" biofuel technology is ready and its market condition stays as the scenario assumed.

If BC was to take the inward-focused strategy, the frameworks used in the IN_POP, IN_CONS and IN_FUEL scenarios can be combined into an integrated biomass utilization strategy which will achieve higher mitigation benefit than the results of the inward scenarios in Fig. 41, that is, to fulfill the domestic demand for various HWP end uses, which increases in proportion to population growth, increase the wood construction shares in the domestic market and use the biomass remaining to displace fossil fuels in the transportation sector. However, this potentially self-sustaining bioeconomy has higher uncertainty around the technology of biofuel which poses greater risk for the province to achieve the determined mitigation targets, compared to the construction option where BC has existing infrastructure and knowledge, which can potentially help make the province a green building material advocate and help capture a larger share of the international long-lived products market. The combined substitution opportunities were further investigated in Ch. 6.

It is important to point out that the combined strategy mentioned above is not the most climate efficient way to use harvested forest resources. Using harvested biomass as biofuel feedstocks only provides 22% of the mitigation benefit per unit of wood compared to construction applications (Tbls. 6, 7). The OU_CONS scenario in Fig. 41 has indicated that even without the substitution benefit, export for construction applications would be the best option, provided that BC can guarantee a global construction market access in the long term and that the current production-based accounting regime remains unchanged. There may be some level of substitution benefit on top of that, from a global climate perspective, under the condition that these future foreign timber constructions were used to substitute for concrete or steel constructions, even though these substitution benefits were not attributed to BC or Canada's emission reports. However, there are also risks regarding whether BC can guarantee the exported products are used in long-term applications. This study revealed that if exported HWPs are not used in applications with an average service life of greater than 32 years, then an inward-focused biofuel strategy would be more beneficial than an export-oriented HWP strategy. Currently, the service lives of BC wood exported to China (with a mass-based average of 5.7 years) and Europe (with a mass-based average of 0 years) are significantly lower than this threshold. From the perspective of unilateral GHG emission reduction targets only, BC would be better off by shifting biomass supply from short-lived exports such as pulp and wood pellets to biofuel production, and mandating that these biofuels displace fossil fuels.

Therefore, potential conflict exists between BC-specific benefits and maximizing the global GHG mitigation outcome. If international collaborations on future wood buildings were in place, BC's harvested wood products sector could make a maximum global mitigation contribution of 66 $MtCO_2e$ $year^{-1}$ (the ALL_CONS scenario). Without these agreements being in place and using the production approach, it is advantageous to BC's GHG balance to adopt a self-sustaining bioeconomy. However, by using less biomass for long-lived high displacement applications, the world achieves less GHG mitigation per unit of roundwood harvested in BC. The development of a construction-focused bioeconomy would need more engineered wood products to be created for the construction sector, which means that more finger-jointing facilities, cross-laminated timber plants and other value-added facilities need to be built. The technology to manufacture engineered wood products is relatively mature, the risk is lower and the required capital investment may be less than building biofuel plants. These value-added downstream facilities can create jobs in addition to the existing lumber- and pulp-dominated bioeconomy in BC. This analysis highlights the far-reaching consequences of international GHG accounting rules for HWP and the need to align them with the desired global outcomes.

4.4 Conclusions

Substitution benefits can provide substantial emission reductions and need to be considered when developing mitigation strategies. In theory, the largest cumulative substitution benefit *from 2016 to 2050* that BC can possibly create through the application of wood constructions under the current harvest projections is approximately 1,296 $MtCO_2e$. However, with the current level of market access, even doubling the domestic market share of wood constructions would only achieve about 7% of this value (88 $MtCO_2e$). Adding the carbon storage benefits, the cumulative mitigation benefit is 231 $MtCO_2e$. On the other hand, a cumulative mitigation benefit of approximately 439 $MtCO_2e$ can be achieved through the use of remaining pulp logs and milling residues after fulfilling the domestic demand as feedstocks for wood-based transportation fuels and substitute fossil fuels, almost twice the benefit of the inward-focused construction strategy. However, this option poses greater challenges for BC to achieve its legislated emission reduction targets because technology and infrastructure to produce the required quantities of liquid transportation fuels from wood are not yet available in BC.

If BC was able to gain access to the international green building market and use its wood products to fulfill demand for sustainable structural material, the long-term foreign carbon storage would generate a cumulative benefit of 953 $MtCO_2e$ between 2016 and 2050. In addition, the associated substitution in the export regions would benefit the global GHG balance. That said, uncertainties exist regarding whether the exported wood products will indeed be used for long-lived construction applications. Exporting wood for short-lived applications would greatly reduce the efficiency of this mitigation strategy and may make it less effective than an inward, self-sustained option that satisfies the domestic demand for various end-uses, encourages structural applications, and substitutes fossil fuels with “drop-in” biofuels.

4.5 Methods

Data were collected from comparative LCA studies that analyzed a more wood intensive building and a less wood intensive building. Two important pieces of information were required to calculate the displacement factor: the whole building bill of materials and the associated embodied emissions. The displacement factor may then be calculated using Eq. 5:

$$DF = \frac{CE_{embodied,lesswoodintensive} - CE_{embodied,morewoodintensive}}{CW_{morewoodintensive} - CW_{lesswoodintensive}} \qquad (5)$$

where, DF is the displacement factor, CE is the embodied carbon emissions collected from the LCA study, and CW is the amount of carbon contained in the wood products used to build the construction. If the LCA study reported the embodied emissions of the buildings, then those CE values were obtained directly. Otherwise the CE is calculated by subtracting the operational emissions from the total GHG emissions.

We collected data from several LCAs that studied different building types (i.e., residential and non-residential) and structural types (i.e., heavy timber, light weight wood frame, concrete and steel), and calculated several displacement factors (Appendix D). These displacement factors were then used to determine the range and the expected values with which a triangular distribution was constructed. A set of 100,000 displacement factors was randomly sampled from the triangular distribution for the uncertainty calculations of emissions avoided by substituting wood for other building materials.

The displacement factor of wood-based transportation fuels was calculated using information gathered from two LCA studies undertaken specifically for BC (Appendix E and F). One of the studies examined the global warming potential of wood-based transportation fuels produced through the pyrolysis pathway [185] and the other examined the hydrothermal liquefaction (HTL) pathway [197]. The data of interest were the amount wood input required per unit of renewable fuel output and the embodied emissions per unit of the renewable fuel. The embodied emissions of the conventional fossil-based fuel were also needed for comparison. The displacement factors were then calculated using Eq. 6:

$$DF = \frac{CE_{renewable} - CE_{conventional}}{CW_{renewable}} \qquad (6)$$

where, DF is the displacement factor, CE is the embodied emissions per unit of fuel, and CW is the amount of carbon contained in the wood input required to produce one unit of renewable fuel output.

Each LCA study contained several scenarios that yielded different displacement factors. Detailed data and calculations are also included in Appendix E and F. In a similar manner to the wood building methodology, these displacement factors were used to construct a triangular distribution and 100,000 samples were randomly drawn for the uncertainty calculation.

As discussed earlier, a valid substitution required a shift of strategy or a change of decision making that caused additional wood to be used in the construction sector or used as a renewable fuel feedstock. The additional wood consumption for buildings and renewable transportation fuels was obtained from the modeling results in Ch. 3. Eq. 7 was used to calculate the avoided emissions.

$$Substitution\ Benefit = E_{avoided} = C_{substitution} \times DF \qquad (7)$$

where, E is the emissions avoided, C is the carbon contained in the end-uses of valid substitution, and DF is the corresponding displacement factor.

Since 100,000 displacement factor samples were established for each wood constructions and wood-based transportation fuels, the calculated avoided emissions ranges were represented by a box plot with minimum, maximum, first quartile, second quantile (median) and third quartile values.

The substitution benefits were then included in the scenario-based mitigation analysis with total mitigation benefit quantified using eq. 8:

$$Mitigation\ Benefit = Storage\ Benefit + Substitution\ Benefit \qquad (8)$$

where a mitigation scenario's storage benefit refers to the reduced HWP emissions compared to the baseline scenario (Eq. 9).

$$Storage\ Benefit = E_{HWP,\ BASE} - E_{HWP,\ SCEN} \qquad (9)$$

The net emissions were calculated using Eq. 10 to demonstrate the emissions reduction by scenarios relative to the business-as-usual baseline.

$$Net\ Emissions = E_{HWP} - E_{avoided} \qquad (10)$$

The threshold service life was estimated using the MitigAna model. The model configurations of the IN_FUEL and OU_CN scenarios were used (the configurations of the OU_EU or OU_CONS scenario can also be used and will reach the same result). We progressively changed the service lives of HWPs exported to China until the emission results equaled the net emissions of the IN_FUEL scenario (Fig. 41, IN_FUEL, 50th percentile value).

5 Forest Sector Mitigation Consequences of Cascading Uses of British Columbia's Postconsumer Wood Products

5.1 Introduction

Harvesting and replanting are ways to sustain strong carbon sinks in the forest while supplying society's need for materials and energy. Wood fiber is a limited and valuable resource, and energy, transportation, building and other sectors seek to reduce their emissions through the use of forest biomass[9]. However, British Columbia (BC)'s harvest volume is expected to continuously decline over the next few decades mainly due to the reduced salvage logging of mountain-pine-beetle killed timber and a reduction in timber supply resulting from large-scale forest fires in recent years [34, 39]. Therefore, society needs to use and reuse the harvested biomass as effectively as possible and the cascading use of wood products is one of means of achieving this goal.

Cascading uses of postconsumer wood[10] are an end-of-life practice that transfers the same woody biomass through a hierarchy of product life cycles [212]. It optimizes the utilization of postconsumer harvested wood product (HWP) commodities by reusing them for the same purpose or by recycling them to a series of lower value or quality applications before final disposal by combustion or in a landfill. Cascading wood use is considered to be more efficient than current practices which are predominantly single use [90].

The use of postconsumer wood in cascades seeks to provide three potential benefits from a carbon perspective: longer carbon retention, reduced harvest intensity, and increased substitution [216, 219]. Recycling HWPs to complete an additional product life cycle extends the service life of the harvested biomass and further delays the release of carbon to the atmosphere. This carbon redirection from

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[9] Examples are EU's wood pellets substitution for coal as a fuel in thermal electricity generation, Boeing's sustainable aviation biofuel project and Canada's tall wood building initiatives.

[10] In this context, postconsumer commodities describe a collection of commodity wood products that are retired from their current end-use. The term includes sawnwood, plywood, OSB and MDF that have reached their end-of-service-lives in residential dwellings and renovation, non-residential buildings, furniture, industrial production and other end uses. It also includes paper products.

burning or decomposition can provide an instant emission reduction from HWPs. In addition, a longer carbon retention in general provides a larger HWP carbon store before the pool reaches saturation (see Ch. 1). It is worth noting that emissions associated with recycling processes also need to be considered in order to understand the overall emission consequences, but their quantification is outside the scope of this study. Potential complications arising from contaminants of HWP such as mechanical fasteners or chemical residues, and the economics of recycling programs are also not addressed here.

After collection and sorting, a proportion of the recycled postconsumer biomass may be used as an additional fiber supply to wood products manufacturing plants. If society's wood consumption remains the same, this implies that the harvest from the forest can be reduced, allowing more standing trees to sequester and store carbon. Alternatively, if the harvest volume remains the same, additional wood products would be available for substituting emissions-intensive non-wood materials and fuels.

The European Union countries have taken the lead on studying this topic. Life cycle analyses (LCAs) have indicated the viability of developing a wood cascade system in Europe and greenhouse gas emission reductions between 7% to 21%, and a harvest savings of 14% to 38% have been reported [219, 343–346]. However, studies have shown that cascading does not always lead to significant climate benefits because the provision of woody biomass is only a small portion of the total environmental impacts of a product's life cycle. For example, chemical additives such as resins and energy consumption during wood products processing can contribute over 50% of the overall GHG emissions [216]. One study has estimated that under a material recycling rate of 14% for postconsumer wood in the EU, cascading use of postconsumer wood products only, on average, increased the displacement factor of wood products by 0.055 kgC kgC^{-1} (cf. in the EU, the average displacement factor of wood products without cascading was estimated to be 1.2 kgC kgC^{-1}) [28, 113].

British Columbia possesses 1.5% of world's forest area and has one of the largest global forest areas per capita at 11.2 hectare (ha) per person [33, 34]. However, this abundance of forest resources, and the consequential ready availability of round wood, might reduce the motivation to recycle postconsumer wood products and historically, over 60% of the retired wood products have been sent to landfills [90]. Very few studies have assessed the cascading uses of wood in Canada. The only study that we are aware of evaluated the carbon retention of the cascading uses of wood using the IPCC's immediate end-of-life emission assumption [347]. The assessment of wood cascading options using more realistic service life values was therefore considered to be worthy of investigation.

The goals of this research were:

1. to model the fate of carbon in wood cascades;
2. to quantify the direct carbon storage and emissions in forests and HWPs;
3. to determine the potential importance of cascading HWP uses within BC's forest sector, climate change mitigation strategy and policy development.

The study's focus was restricted to postconsumer solid and composite wood products. Paper was excluded from the cascading system as the paper recycling rate in BC is already high and it was assumed that only a marginal benefit could be achieved beyond the current level. Paper recycling rates in Canada and BC have reached approximately 70% [90, 348–350], although the percentage of recycled pulp content is dependent on the paper grade and the end use of the paper product [348, 350, 351]. The final phase of the wood cascade is either landfill or incineration for energy. Approximately 88% of BC's electricity comes from hydro generation which creates lower GHG emissions than combusting wood [317, 331]. At the time this research was conducted, no information on converting postconsumer wood to liquid transportation fuels was found. Due to the level of contaminants in postconsumer wood, it is unlikely that this technology will be commercially available in the foreseeable future. Consequently, the substitution benefit that arises from combusting cascaded wood to generate energy was not the focus of this study.

5.2 METHODS

The cascading modules for postconsumer HWPs were inserted in the MitigAna model. The schematic flow diagram of the cascading module is presented in Fig. 42. Some stages that are included in the model are omitted from the diagram to avoid overcomplicating the diagram (e.g., commodity production and end-use stages. See Fig. 3 and 4 in Ch. 2). This module was inserted between the end-use and landfill stage (Fig. 4 in Ch. 2), and linked back to the commodity production stage (Fig. 3 in Ch. 2). Postconsumer commodities (i.e., sawnwood, plywood, OSB, MDF and particleboard) were collected from residential dwellings, non-residential buildings and furniture, and were sent to different destinations depending on the scenario. Wood commodities used for industrial production purposes (e.g., concrete casing and pallets) were not included in the cascading system due to the high wear and tear of this use category and the observation that the retired wood cannot be salvaged for other applications other than energy or landfilling. These categories were therefore treated as single-use products.

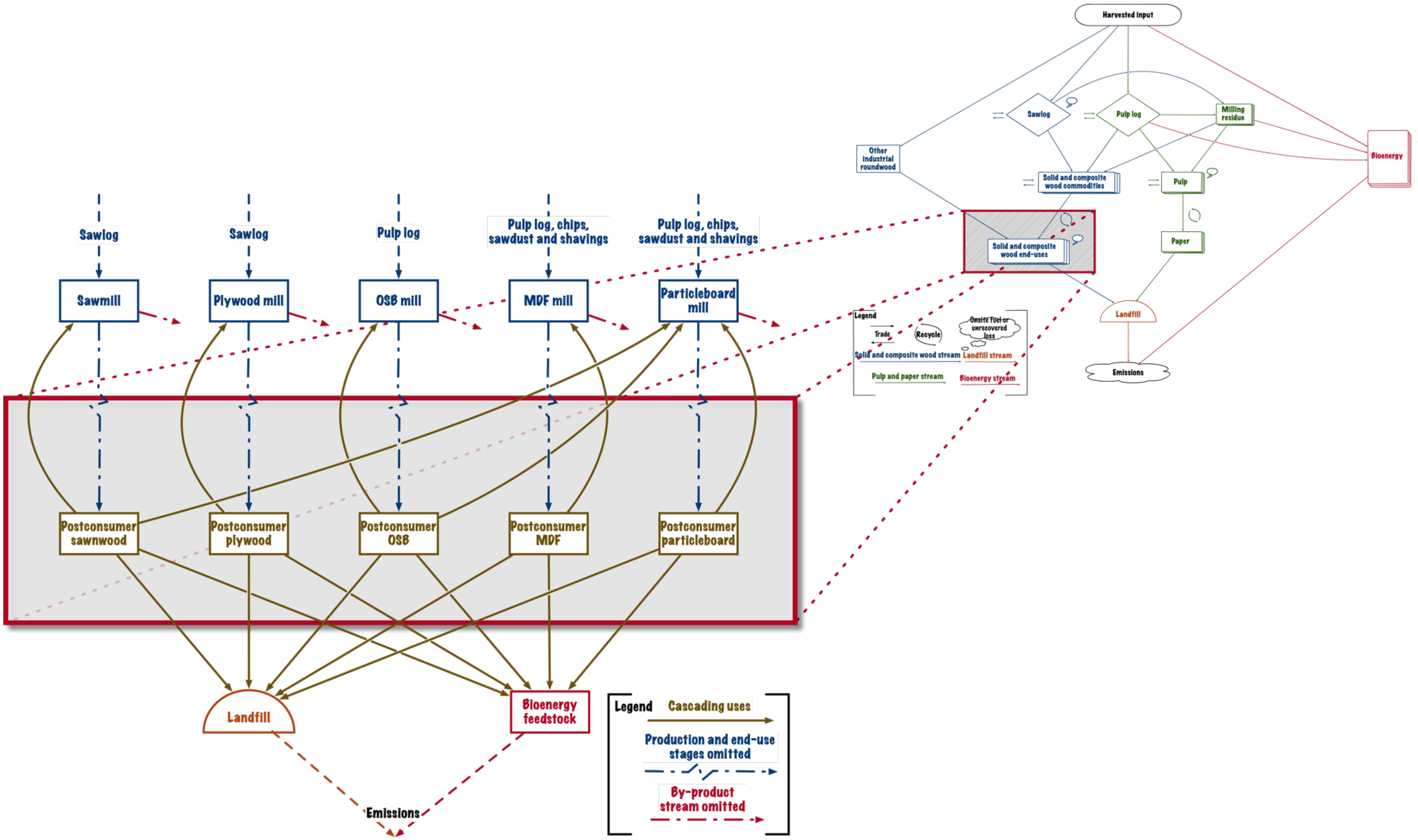

Figure 42. Schematic flow diagram of cascading uses of solid and composite wood products.

This module was applied to three jurisdictions in the MitigAna model: Canada, US and Japan. China and the European Union (EU) were intentionally excluded from the application of this module. China was omitted because most wood products were used as temporary construction or packaging materials (e.g., concrete casing and pallets) with high wear and tear which caused their service lives to be short (see Table 3 in Ch. 2). Typically, these end-uses would use lumber and panel products repeatedly over a three-month period [92]. In the MitigAna model described in Ch. 2, half-lives for these applications in China already considered these repeated reuse and recycling phase and it was determined that applying cascading to China's use of these products would not yield higher recycling rates than those previously incorporated in the model. The EU was excluded because their major import from BC is wood pellets for energy generation and this step is already at the lowest level of the cascade.

5.2.1 CASCADING-USES SCENARIOS

Two cascading scenarios were created, in addition to a baseline scenario, to examine the GHG emission consequences of cascading uses of wood. The design concept was to evaluate the following three scenarios:

1. the baseline scenario (BASE) that could be viewed as the lower-bound situation in which no new cascading practices were adopted. The baseline scenario used in this study was the same one investigated in Ch. 3 and Ch. 4. The end-of-life events in this scenario involved sending all postconsumer commodities to landfills and the carbon in these products was assumed to be instantaneously oxidized in the landfill in accordance with the IPCC default assumption [47]. This assumption is likely to be a conservative estimation because research has shown that emissions from wood products in landfills have been significantly overestimated [290]. However, a detailed modeling of HWPs landfills is outside the scope of this study.

2. the maximize reuse scenario (REUSE), which was a high recycling rate scenario designed to demonstrate the upper-bound of cascading technologies. The REUSE scenario assumed that during the end-of-life event, 85% of the postconsumer commodities were sent to corresponding commodity mills to remanufacture for reuse, and 15% of the postconsumer commodities were sent to landfills.

3. the achievable cascade scenario (CASCD) which was a more practical recycling scenario with realistic technological requirements that may be expected to be achieved in the near future. The CASCD scenario was based on systems investigated by Vis et al. [212], Mantau [352] and

Höglmeier et al. [216, 225] with adjustments made to the modeling categories. The cascading allocations were assumed as follows:

- Postconsumer sawnwood
  - 5% -> sawmills for remanufacturing
  - 30% -> particleboard manufacturing
  - 35% -> bioenergy feedstock
  - 30% -> landfill
- Postconsumer plywood
  - 70% -> bioenergy feedstock
  - 30% -> landfill
- Postconsumer OSB
  - 10% -> particleboard manufacturing
  - 60% -> bioenergy feedstock
  - 30% -> landfill
- Postconsumer MDF
  - 10% -> MDF remanufacturing
  - 60% -> bioenergy feedstock
  - 30% -> landfill
- Postconsumer particleboard
  - 5% -> particleboard remanufacturing
  - 65% -> bioenergy feedstock
  - 30% -> landfill

This scenario served as a first approximation of the cascading system that may be achievable in the near future in BC. The cascading allocations outlined above should be feasible in BC based on the recycling and utilization rates reported in the European Union. The allocation in this scenario is expected to represent the level of the present cascading use technology with the issues of collection, sorting, treatment, remanufacture and commercialization factored in. Of the 52 million m^3 postconsumer wood products in the EU in 2010, on average 30% were channeled into wood processing facilities for remanufacturing, 31% were sent to landfills, and 39% were recovered for energy [212, 352, 353]. It is important to point out that Scandinavian countries have higher remanufacturing and energy recovery rates because landfilling wood has been banned [354] (e.g., Finland has a remanufacturing rate of 45% and the rest for energy [212]). Case studies have indicated that approximately 50% of the construction and demolition postconsumer wood were untreated and up to 70% of the woody component in buildings can be reused or cascaded [212]. It was estimated that 25% of the recovered wood from building demolition in Germany is suitable for reuse and 84% of this 25% can be used for high-value secondary applications [225]. Postconsumer wood furniture was reported to have a 40% recovery and 4% reuse rate [212]. The particleboard industry has utilized most of the recycled postconsumer products in the EU which comprises 30% of the industry's biomass input [212].

5.2.2 *Cascading assumptions*

From a modeling perspective, postconsumer products that are collected, fed back to the mills and remanufactured into new products could potentially cause infinite loops (Fig. 42). Therefore, as the wood products became "postconsumer" (i.e., retired from their current end-use), the collection and feedback events of the recycled biomass were assumed to happen in the same year, whereas the remanufacturing events that produced next-life products from the recycled biomass were assumed to happen in the next year. Postconsumer products that were sent to bioenergy feedstock and landfills would not cause infinite loops and their events were therefore simulated in the current year.

5.2.3 *Study period*

In the previous two chapters, a study period from 2016 to 2050 was used because we wanted to examine the emission consequences caused by a change of utilization and trading strategies on future emissions[11] (see Ch. 3). Cascading uses of wood, however, deal with end-of-life practices. The HWPs that reached their end-of-life between 2016 and 2050 were harvested during an earlier period. Therefore, 1990 was chosen as the initial year for this study. This starting year aligns with the Canadian National Inventory Reports [46] from which the data after 1990 have been frequently maintained and updated, and it is convenient for comparing results.

5.3 Results

The 2020, 2030 and 2050 emissions of HWPs harvested in BC for the REUSE and CASCD scenarios by consuming jurisdictions compared to the BASE scenario are presented in Tbl. 10.

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[11] It takes two years for data processing and reporting, therefore in 2018 the latest data available is for 2016.

Table 10. 2020, 2030 and 2050 GHG emissions from HWPs harvested in BC under the BASE, REUSE and CASCD scenarios. Unit: $MtCO_2e$ $year^{-1}$. DM: domestic market, US: the United States, CN: China, JP: Japan, EU: the European Union and OT: other jurisdictions.

$MtCO_2e$ $year^{-1}$	2020			2030			2050		
	BASE	REUSE	CASCD	BASE	REUSE	CASCD	BASE	REUSE	CASCD
DM	18.1	17.2	17.8	17.2	16.1	16.9	16.6	15.3	16.4
US	11.7	9.8	10.7	12.5	10.5	11.3	13.2	11.5	12.2
CN	10.9	11.0	10.9	10.1	10.3	10.2	9.6	9.8	9.6
JP	3.1	2.7	2.8	3.1	2.8	2.9	3.2	2.9	3.0
EU	3.4	3.5	3.5	3.1	3.2	3.1	2.9	3.0	2.9
OT	3.9	3.9	3.9	3.6	3.6	3.6	3.3	3.4	3.3
Total	51.1	48.1	49.6	49.6	46.5	48.0	48.8	45.9	47.4

The general trend of HWP emissions was similar among the BASE, REUSE and CASCD scenarios. Both REUSE and CASCD scenarios achieved emission reductions compared to the BASE. By 2050, the REUSE scenario achieved an emission reduction of 1.3 $MtCO_2e$ $year^{-1}$ in the domestic market, 1.7 $MtCO_2e$ $year^{-1}$ in the US market, and 0.3 $MtCO_2e$ $year^{-1}$ in the Japanese market; the CASCD scenario achieved 0.2 $MtCO_2e$ $year^{-1}$ in the domestic market, 1.0 $MtCO_2e$ $year^{-1}$ in the US market, and 0.2 $MtCO_2e$ $year^{-1}$ in the Japanese market (Tbl. 10). The REUSE scenario was expected to have lower emissions than the CASCD scenario because of its higher recycling rate. The emissions in China, EU and other jurisdictions were expected to slightly increase (i.e., 0.1 ~ 0.2 $MtCO2_e$ $year^{-1}$) due to the small increased exports provided by cascading fiber supply. Fig. 43 presents the cumulative emission differences of REUSE and CASCD scenarios relative to the BASE scenario. The emission reduction rates initially increased with time and then decreased. In the REUSE scenario, the annual emission reduction increased from 0 to 3.19 $MtCO_2e$ $year^{-1}$ by 2033 and subsequently decreased to 2.86 $MtCO_2e$ $year^{-1}$ by 2050. In the CASCD scenario, the reduction increased to 2.0 $MtCO_2e$ $year^{-1}$ by 2028 and then decreased to 1.2 $MtCO_2e$ $year^{-1}$ by 2050. If the harvest level remained relatively stable after 2050, the emission reduction rate would be expected to continue declining.

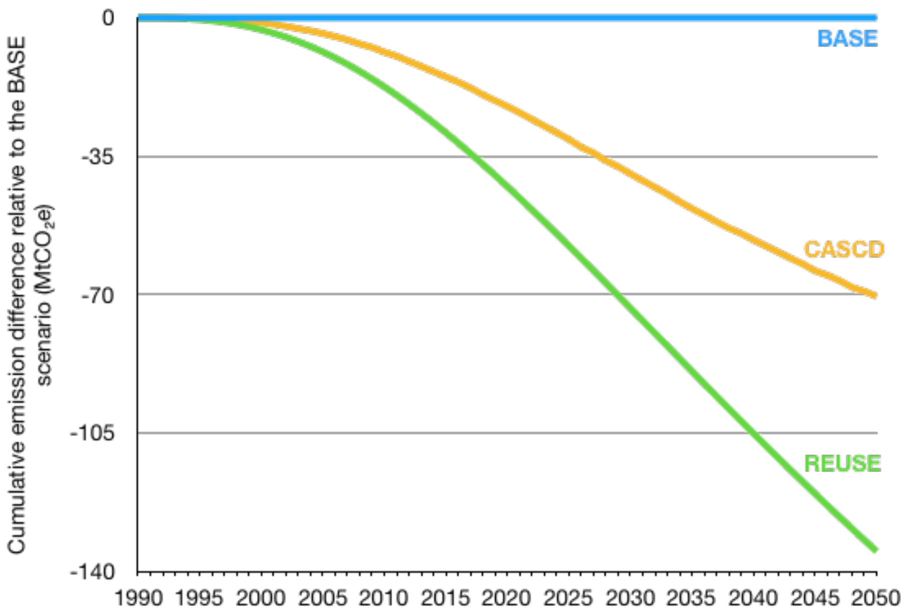

Figure 43. Cumulative emission differences of cascading-uses scenarios relative to the baseline. The blue line at y = 0 indicates the BASE scenario.

Fig. 44 presents the cumulative emissions from 1990 to 2050 by forest products category. The solid and composite product category is subdivided by the consuming market, in order to show the geographic location of the emissions.

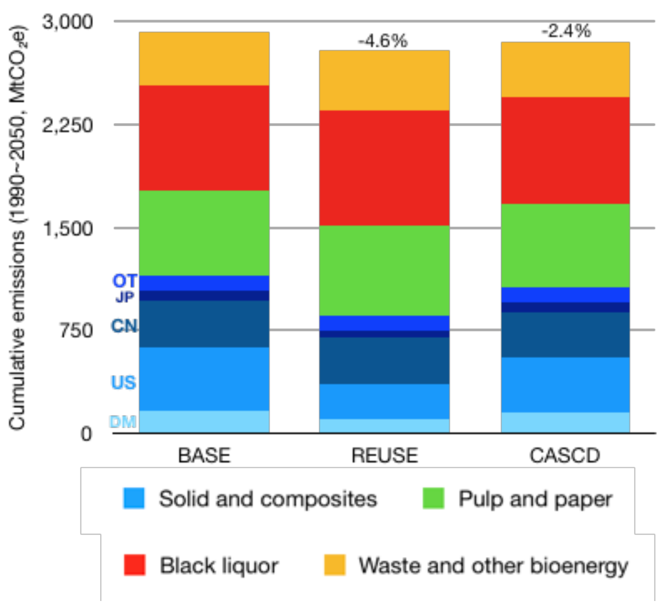

Figure 44. A comparison of cumulative emissions of cascading-uses scenarios by forest products category. Solid and composite products are subdivided into consuming markets. DM: domestic market, US: United States, CN: China, JP: Japan, OT: other markets.

In the REUSE scenario, the total cumulative emissions between 1990 and 2050 were reduced by 4.6% (i.e., 135 $MtCO_2e$) and by 2.4% (i.e., 70 $MtCO_2e$) for the CASCD scenario (Fig. 44). These cumulative emission reductions differed by products and markets, they decreased in some product categories and increased in others (Fig. 44). In the REUSE scenario, cumulative emissions from solid and composite wood products consumed in the domestic market were reduced by 60 $MtCO_2e$ (i.e., a 36.5% reduction compared to equivalent emissions in the BASE scenario, Fig. 44); Cumulative emissions from these categories of wood products consumed in the US market over the same period, declined by 206 $MtCO_2e$ (i.e., 44.4%), and those in the Japanese market by 36 $MtCO_2e$ (i.e., 46.8%). In the CASCD scenario, cumulative emissions for the solid and composite wood products consumed in the domestic market between 1990 and 2050 decreased by 11 $MtCO_2e$ (i.e., 6.8%). Equivalent emissions in the US market decreased by 68 $MtCO_2e$ (i.e., 14.6%); and those in the Japanese market by 12 $MtCO_2e$ (i.e., 15.8%). Emissions increased in product categories that received input from cascading wood uses. The majority of carbon was emitted through paper products and bioenergy combustion, including black liquor emissions arising from the manufacture of chemical pulp and wood pellets exported to the EU to generate electricity. Black liquor accounted for 26% to 30% of the total HWP emissions (Fig. 44) and wood pellets exported to the EU accounted for 7.0% to 7.5% (Tbl. 10)

The additional biomass supply to solid and composite wood products mills resulting from each scenario used to assess the cascading uses of wood is presented in Tbl. 11.

Table 11. The base and the additional biomass supply to mills generated by each scenario evaluating the cascading uses of wood (in $MtCO_2e$), cumulative from 1990 to 2050.

Fiber inputs by mills category	BASE	REUSE	CASCD
Sawmills	2,805	+ 296	+ 16
Plywood mills	304	+ 38	+ 0
OSB mills	134	+ 33	+ 0
MDF mills	20	+ 7	+ 1
Particleboard mills	10	+ 0	+ 102
Total	3,273	+ 375 (+ 11.4%)	+ 119 (+ 3.6%)

The REUSE and CASCD scenarios provided 11.4% and 3.6% more total biomass input than the baseline scenario, respectively. Particleboard mills received a negligible amount of additional biomass input in the REUSE scenario because BC currently does not mass-produce particleboard [35] and therefore only a small amount can be reused in this scenario. In contrast, the CASCD scenario allocated postconsumer sawnwood, OSB and particleboard itself to particleboard remanufacturing and therefore generated an additional 102 $MtCO_2e$ biomass supply. In the CASCD scenario, plywood and OSB mills received no biomass because the scenario settings did not direct any postconsumer products to plywood or OSB mills (see Methods section).

In 2016, British Columbia's reported emissions from HWPs were 43 $MtCO_2e$ $year^{-1}$ [10]. The average emissions estimated for the BASE scenario were approximately 48 $MtCO_2e$ $year^{-1}$ (i.e., 12% difference). The structure of the MitigAna model and retention curves are different from the ones used in the provincial emission report [10]. In addition, this study focused on future emissions between 2016 and 2050 and used harvest projections, whereas the provincial emission report estimated the contemporary emissions between 1990 and 2016. Considering these factors, the results of the model were considered to have an adequate agreement with the previously reported value [10].

5.4 DISCUSSION

This study designed the CASCD scenario to be a potentially achievable cascading system in the near future. However, the direct carbon retention benefit of this system was relatively small as it achieved only a 2.4% reduction in HWPs emissions compared to the BASE scenario (i.e., on average a reduction of 1.16 $MtCO_2e$ $year^{-1}$) between 1990 and 2050 (Fig. 44). For comparison, the province's current emissions from HWPs are 43 $MtCO_2e$ $year^{-1}$ [10]. This analysis assumed that the cascading wood use was implemented starting in 1990 (though products suitable for cascading uses only reached their end-of-life transition in later years in the simulation) and that cascading wood use was implemented in both domestic and export markets. Even with these assumptions, the mitigation benefits remained small compared to other opportunities.

Another climate benefit of the cascading uses of wood is the "avoided harvest". As shown in Tbl. 11, recycled postconsumer products became effective biomass supplies to the mills, which potentially means less roundwood harvest would be required from the forests, potentially allowing the trees to continue to grow and sequester carbon from the atmosphere. It is estimated that the "avoided harvest" in the CASCD scenario can enable an additional sequestration of 1.1 $MtCO_2e$ $year^{-1}$ at the end of 2050[12], equivalent to 3.6% additional annual carbon removal from the atmosphere by BC's Timber Harvest Land Base.

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[12] BC's managed forests sequester 28 $MtCO_2e$ $year^{-1}$ from the atmosphere [46]. BC has 22 million hectares (ha) of managed forests and the average wood volume is 200 m^3 ha^{-1} [33, 355]. Species-

The province's current emissions from all the other sectors, excluding forest management are 62 $MtCO_2e$ $year^{-1}$ [10]. The 2018 Clean BC strategic plan described proposed actions to achieve 18.9 $MtCO_2e$ $year^{-1}$ emission reduction in these sectors by 2030 [60], which is about 75% of the legislated 2030 reduction target of 25 $MtCO_2e$ $year^{-1}$ [7]. The province has identified waste reduction and the development of a circular economy as the potential areas for the remaining reduction of 6.1 $MtCO_2e$ $year^{-1}$ [60] and the cascading uses of wood may be able to contribute to these goals. As shown in Tbl. 10, by 2030, the CASCD scenario would achieve 1.6 $MtCO_2e$ $year^{-1}$ emission reduction through cascading uses of wood and 1.1 $MtCO_2e$ $year^{-1}$ through avoided harvest, or in total 44% of the remaining reduction requirement. However, it is worth noting that the CASCD scenario assumed that the domestic, US and Japanese markets all adopted the same system for cascading wood. The constrained domestic market size results in only 0.3 $MtCO_2$ $year^{-1}$ emission reduction by 2030, or 5% of the remaining reduction requirement.

The scenarios in this study did not consider the progressive development of infrastructure and the improvement of technology with time. It also assumed the that the cascading system evaluated in each scenario could be implemented instantaneously. While we consider that the recycling rate outlined in the CASCD scenario should be achievable in the near future, at this stage, establishing an actual cascading system still faces substantial technological, financial and cultural challenges [215, 220] (see Ch. 1). In addition, the emission reductions were achieved by assuming that the domestic, US and Japanese markets all implemented an identical system for cascading wood. As a major wood products exporter, BC's role in creating a common cascading scheme is actually very limited, as most of the cascading events will take place outside of BC, in a similar manner experienced by Finland [356].

As shown in Fig. 44, there is only a 2.2% emission reduction between the CASCD and REUSE scenarios, but moving between scenarios requires that the recycling rate increases from less than 30% to 85% (see Methods section), indicating that a diminishing rate of return exists for the cascading uses of wood. If the domestic, US and Japanese markets were to improve the recycling rate achieved in the CASCD scenario to the level of the REUSE scenario, the additional emission reductions attained are approximately 1.06 $MtCO_2e$ $year^{-1}$. For comparison, a total of 29 $MtCO_2$ $year^{-1}$ on

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weighted average roundwood density is 0.39 oven-dry tonnes (o.d.t) m^{-3} and carbon content of wood is 0.5 tC $(o.d.t\ wood)^{-1}$ [46]. The CASCD scenario yielded 119 more biomass supply cumulatively from 1990 to 2050, respectively (Tbl. 11).

average was released from paper products and bioenergy combustion including black liquor emissions arising from manufacturing chemical pulp (11 $MtCO_2$ $year^{-1}$, Fig. 44) and wood pellets exported to the EU market (3.3 $MtCO_2$ $year^{-1}$). This study has highlighted the climatic benefits of implementing a relatively simple and cost-effective wood cascading system and demonstrated that high wood recycling rates have marginal additional benefits, considering the technological, financial and cultural challenges. Greater mitigation benefits would be achieved through restricting wood exports for short-lived uses. Black liquor accounted for 26% of the total HWP emissions (Fig. 44) and wood pellets exported to the EU accounted for 7% (Tbl. 10), which are substantially larger than the upper-bound climate benefit that cascading uses of wood can achieve (i.e., the REUSE scenario).

In Canada, over 60% retired solid HWPs are sent to landfills [90] and the carbon contained are assumed to be emitted instantly. The BASE scenario in this study and the Canadian National Inventory Report both modeled their fate in this manner [46]. However, there are actually three major HWP end-of-life practices: landfilling, use as an energy feedstock, and cascading. As the uncertainties in the production and use stages have been significantly reduced by recent and ongoing research studies, the focus of future studies should be on investigating these end-of-life options.

The cascading uses of wood are considered to be a more efficient way of using the forest resources than the single use strategy that is currently implemented by society. In most cases, jurisdictions should prioritize material uses (by positioning them on higher cascade levels) over energy uses or landfilling (by positioning them at lower cascade levels) [222]. This utilization strategy would extend the service life of forest biomass, and thereby increasing the carbon retention time, before emitting the carbon back to the atmosphere. A consequence of prolonging the service life is that there is a delay in wood becoming available as a bioenergy feedstock. One of the challenges of wood-based renewable transportation fuels is the limited availability of biomass supply [174, 184, 185]. Collecting the postconsumer HWPs for biofuel feedstock may be an effective and straightforward solution. However, postconsumer products are likely to contain contaminants from the previous uses, such as chemical residues and metal fasteners, making the conversion of postconsumer biomass to "drop-in" biofuels more challenging [181]. In addition, whether this approach will provide a substitution benefit is uncertain as the collection, sorting, treatment and transportation phases will generate more emissions that may offset the climatic benefits of recycling. This study did not quantify process emissions associated with recycling as these should be part of an LCA. To date, there has been no credible LCA study on postconsumer HWPs for renewable transportation fuels. This kind of analysis and information would greatly assist technology and policy development.

Several EU studies have indicated that the substitution benefit of cascading uses of wood for fossil fuels in electricity generation can be quite significant compared to direct carbon storage benefit from material use [219, 343, 357]. However, BC mainly uses hydropower for electricity production and substituting wood pellets for hydro is likely to provide negligible to negative climate benefit. This option should be further examined for other provinces in Canada, especially for those with fossil fuel combustion facilities for electricity generation.

Due to the complexity and uncertainty of decomposition in the landfills, most HWP models do not have a complete landfill module that realistically quantifies the actual landfilling processes. Sensitivity analysis has indicated that most of the landfill parameters can have a significant impact on GHG emissions [358]. Therefore, because of a lack of detailed research on the two predominant end-of-life options for wood (i.e., bioenergy and landfill), this research is unable to determine the best end-of-life strategy in BC.

5.5 CONCLUSIONS

Despite the challenges of implementing the cascading uses of wood, this study finds that this strategy is able to provide BC with an average HWP emission reduction of 1.16 $MtCO_2e$ $year^{-1}$. Additional mitigation benefits may be achieved through the potential resulting reduction in harvest volume (1.1 $MtCO_2e$ $year^{-1}$ by the end of 2050). BC should initially focus on implementing a simple and cost-effective wood cascading system instead of pursuing more sophisticated technology and infrastructure to optimize the wood recycling rate. This study showed that increasing the recycling rate from less than 30% to 85% yielded only a 2.2% further reduction in total emissions and revealed that a diminishing rate of return exists for the cascading uses of wood. The attainment of high recycling rate delays the availability of postconsumer wood products as feedstocks for a bioenergy and only generates marginal additional GHG benefits. Greater mitigation benefits would be achieved by restricting short-lived wood uses, especially chemical pulp and wood pellets. The fate of wood carbon in the landfill and mitigation benefits of postconsumer wood as a renewable transportation fuel feedstock substituting for fossil fuels need to be further investigated to determine the best end-of-life strategy.

6 A Vision for the BC Forest Sector that Combines Mass-timber Construction and Biofuel Production to Contribute to Domestic Greenhouse Gas Emission Reduction Targets

6.1 Introduction

Biomass harvested from sustainably managed forests has a lower climate impact than most other raw materials used by developed societies. However, such biomass has limited availability and several sectors, including construction, paper and bioenergy, are competing for access to this resource (e.g., [294, 359, 360]). The previous chapters in this thesis have demonstrated that various harvested wood products (HWPs) manufacturing pathways in BC can result in substantially different emission consequences at the provincial, national and global scale. Using HWPs as building materials provides the largest climate benefit per unit of biomass from both a carbon storage and a substitution perspective (Ch. 3 and 4) because long-lived wood products combine two key features: long carbon retention and high displacement of other emissions-intensive materials such as concrete and steel. From the perspective of emission reduction targets, construction uses, whether they are single-, multi-family residential dwellings or non-residential buildings and infrastructures should be positioned as highest priority HWP end use. However, the domestic market for construction HWPs is relatively small and its growth rate is constrained. This application would therefore only contribute an HWPs storage benefit of approximately 4.1 $MtCO_2e$ $year^{-1}$ between 2016 and 2050, and a substitution benefit of 2.5 $MtCO_2e$ $year^{-1}$, on average compared to the baseline scenario (see the results of the IN_CONS scenario in Tbl. 9, Ch. 4).

If British Columbia (BC) was to move to a bioeconomy that prioritizes wood construction, it would have to rely on accessing foreign markets in order to consume all the structural HWPs manufactured. In these circumstances, the US and Chinese construction markets would need to be accessed as they are the only markets large enough to absorb the potential exports from BC. The respective sizes of the US and Chinese residential construction markets in floor area are approximately 177 million m^2 $year^{-1}$ [315] and 2 billion m^2 $year^{-1}$ [305]. However, the growth of BC's wood in construction applications in these two countries has been slow. Foreign market penetration initiatives for wood-frame buildings have not demonstrated a significant increase for the past decades. For example, the share of BC's wood in the US timber construction market had decreased from approximately 20% in 2006 to 15%

in 2016 [94]. The floor area of wood constructions built in China in 2018 using Canadian wood was 842,062 m^2 $year^{-1}$ [83], significantly lower than the floor area requirements of 140 million m^2 $year^{-1}$ modeled in the OU_CONS scenario (see Ch. 3). In addition, the Canada–US Softwood Lumber Dispute and the Sino-Canada trade tensions can further hinder the realization of this wood construction-focused bioeconomy plan.

On the other hand, the emission consequences in the export market varied significantly depending on how the importing nation utilized BC's exported HWPs. If the exported HWPs were not being used for long-lived purposes but for short-lived applications such as concrete casing, paper products and bioenergy, the foreign emissions would be 3-fold higher than if the same amount of biomass was used as building materials (cf. the OU_CONS, OU_CN and OU_EU scenarios in Ch. 3). Because a production-based approach is used in the agriculture, forestry and other land use (AFOLU) sector, BC needs to report these foreign emissions [47, 48]. However, a consumption-based approach is used in the energy sector [101], therefore the substitution beneficiary is usually the importing country due to the reduced consumption of fossil fuels in that jurisdiction (see Ch. 4). Although the exported HWPs can provide a foreign storage benefit, a threshold service life of approximately 32 years exists (estimated in Ch. 4) below which the foreign storage becomes less beneficial than using the biomass to create biofuels that substitute for domestic fossil fuel consumption (cf. the IN_FUEL, OU_CN and OU_EU scenarios in Fig. 3, Ch. 4). Apart from the US and Japan, BC's other trading partners mostly use HWPs for applications with a lower service life than the 32-year threshold (see service lives section in Ch. 2). Mitigation analyses have shown that shifting exported HWPs from short-lived-use jurisdictions to the domestic market resulted in positive mitigation benefits in all the inward-focused scenarios examined (cf. the IN_POP, IN_CONS and IN_FUEL scenarios to the OU_CN and OU_EU scenarios in Fig. 3, Ch. 4), even if the domestic substitution benefits were not accounted (Fig. 12, Ch. 3). It is worth reemphasizing that the utilization of harvested biomass as biofuel feedstocks is a suboptimal solution that provides 22% of the mitigation benefit per unit of wood compared to construction applications[13], however, if the exported HWPs cannot be guaranteed to be used in long-lived applications, BC may need to explore inward-focused biofuel substitution options and Ch. 3 has

[13] For construction applications, 1 tC in wood has 1 tC storage benefit and 1.03 tC substitution benefit; for biofuel feedstocks, 1 tC in wood has no storage benefit and 0.45 tC substitution benefit (Ch. 4).

shown that the domestic market for wood-based “drop-in” biofuels is potentially capable of consuming all the biomass that is currently exported for short-lived uses.

The HWP mitigation strategy for BC is clear: increase the market share of wood construction and reallocate fiber from pulp and paper and other short-lived uses to renewable transportation fuels production to displace fossil fuels. Both actions have been outlined in the CleanBC plan [60]. However, the current action plan is not sufficient to achieve the legislated targets. The goal of this study was to examine the potential climate benefits of an inward-focused, construction-dominated and biofuel-subordinated bioeconomy, which, based on the results of the earlier chapters, is practically the best forest sector based mitigation that BC could develop with an inward-focused bioeconomy. This chapter analyzed this bioeconomy strategy from a GHG emission perspective, and the economic implications were not assessed.

6.2 METHODS

Any changes in consumption arising from a regional mitigation strategy may be accompanied by some degree of carbon leakage[14] [230]. Carbon leakage is an important consideration for policy design but is also highly uncertain and difficult to measure. This research did not consider a detailed quantification of leakage. That said, this study acknowledges the potential impacts of carbon leakage and as a first step, aims to avoid relocating emissions arising from domestic market demand to the other regions [230]. For example, if BC was to use HWPs only for construction and transportation biofuel in the domestic market, the demand for the other end-uses would have to be met through imports from other regions and as a result, BC would relocate the emissions arising from, for example, paper products and black liquor to other jurisdictions. Therefore, domestic HWPs demand for various end uses, other than construction and biofuel, was also considered in our inward-focused, construction- and biofuel-based scenario (IN_PCF). This scenario assumed that

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[14] Carbon leakage is the component of emissions reductions in one jurisdiction that may be offset by an increase in the emissions in another jurisdiction [230]. This may occur through relocation of energy-intensive production (such as pulp manufacturing) to another country. On most occasions, leakage has a negative effect and offsets the mitigation effort. Nevertheless, there may be situations that lead to additional GHG emission reductions outside a project’s system boundary, or positive leakage.

1. The domestic HWPs demand for various end-uses increased in proportion to population growth. This included the domestic demand for solid and composite wood, paper and bioenergy products in construction, renovation, furniture, industrial production, graphics paper, paperboard, tissue, biofuels, firewood and wood pellets.

2. The domestic demand for residential and non-residential constructions increased in proportion to household growth and the domestic market share of wood construction was doubled. This implied that the wood-frame market shares of residential dwellings and non-residential buildings were roughly 100% and 50% for BC respectively, and 60% and 20% for the rest of Canada. This assumption would increase the domestic consumption of the long-lived applications of sawnwood (including CLT etc.), plywood (including laminated veneer lumber (LVL) etc.), OSB (including oriented strand lumber (OSL) etc.), MDF and particleboard.

3. The remaining sawnwood and plywood were exported with the allocation partitions the same as used by the BASE scenario in Ch. 3 and 4. For example, 65% of the sawnwood export was to the US, 21% to China, 8% to Japan and 6% to other jurisdictions [190, 361]. The remaining amounts of OSB, MDF and particleboard were exported if their end-uses have service lives longer than 32 years.

4. The remaining pulp logs and milling residues were used to produce "drop-in" biofuels and displaced fossil fuels in the transportation sector.

Cascading uses of wood studied in Ch. 5 were not included in the IN_PCF scenario. Cascading uses of wood may be able to provide on average 1.16 $MtCO_2e$ $year^{-1}$ emission reduction from wood products harvested in BC between 1990 and 2050 (i.e., a 2.7% reduction from the 2016 HWP emission level of 43 $MtCO_2e$ $year^{-1}$). Achieving these reductions required the same cascading system applied in the domestic, US and Japanese markets. The IN_PCF scenario is an inward-focused scenario with a study period between 2016 and 2050 and a substantial amount of harvested biomass was used to produce biofuels, the benefit of cascading uses of wood would be less than 0.09 $MtCO_2e$ $year^{-1}$ (less than 0.2% reduction from the 2016 HWP emission level of 43 $MtCO_2e$ $year^{-1}$). Therefore, the marginal benefit of cascading uses of wood does not justify their inclusion in this chapter.

6.3 Results

Fig. 45 shows the annual emission trajectory of the IN_PCF scenario generated from the model run.

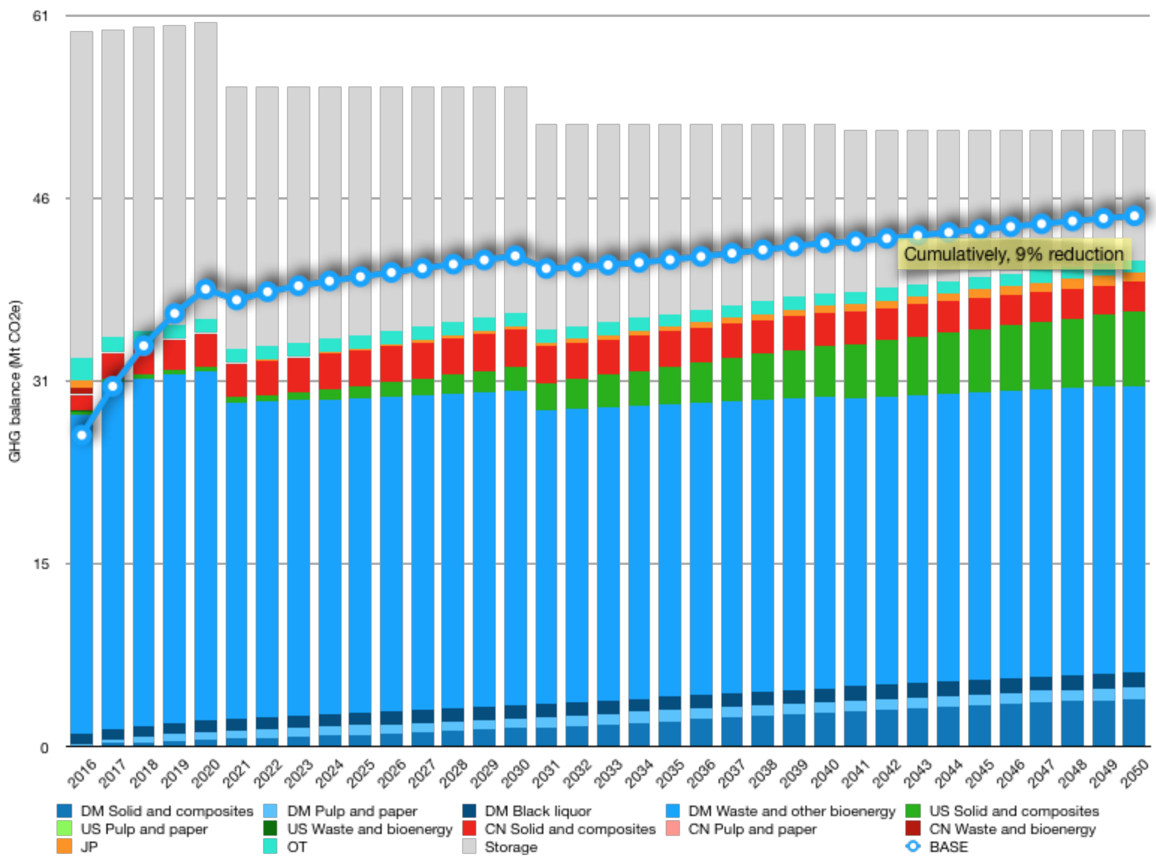

Figure 45. Annual GHG balance of HWPs harvested in BC from 2016 to 2050 of the IN_PCF scenario. Blue series are emissions from HWPs consumed domestically (DM); greens - US; reds - China (CN); orange - Japan (JP); pink - EU; cyan - other jurisdictions (OT); grey is the net carbon storage (i.e., total annual harvests minus total annual emissions); blue line with markers is the total emissions of the BASE scenario listed here for comparison; yellow text box indicates the cumulative difference compared to the BASE scenario.

The emissions from HWPs in the IN_PCF scenario were higher for the first three years (i.e., 2016~2018) than the BASE scenario and then became lower from 2019 to 2050. The reduced emissions were mainly due to the increased proportion of HWP applications in all longer-lived end-use categories in the domestic region but in particular, in the construction sector. Consequently, less wood was used for short-lived purposes. Woody biomass that was consumed as paper or bioenergy in the foreign regions in the BASE scenario was instead converted to transportation biofuels to replace fossil fuels in the domestic market in the IN_PCF scenario (Fig. 45). The emissions in the first three years were higher than the BASE scenario, because the service life of paper, packaging, shipping products and industrial uses was about 1 to 3 years. In the IN_PCF scenario, the carbon in the biofuels was released the year of harvest. In the BASE scenario, most of the carbon in the above-mentioned short-lived products started to be released to the atmosphere after 3 years. As the short-lived pools became saturated, these emissions became relatively stable, which was the time that the IN_PCF scenario would emit less than the BASE scenario. Cumulatively, the IN_PCF scenario resulted in 9% less emissions than the BASE scenario.

The results of the IN_PCF scenario compared to the results of the scenarios presented in Ch. 3 and 4 are presented in Fig. 46, Tbl. 12, and Fig. 47.

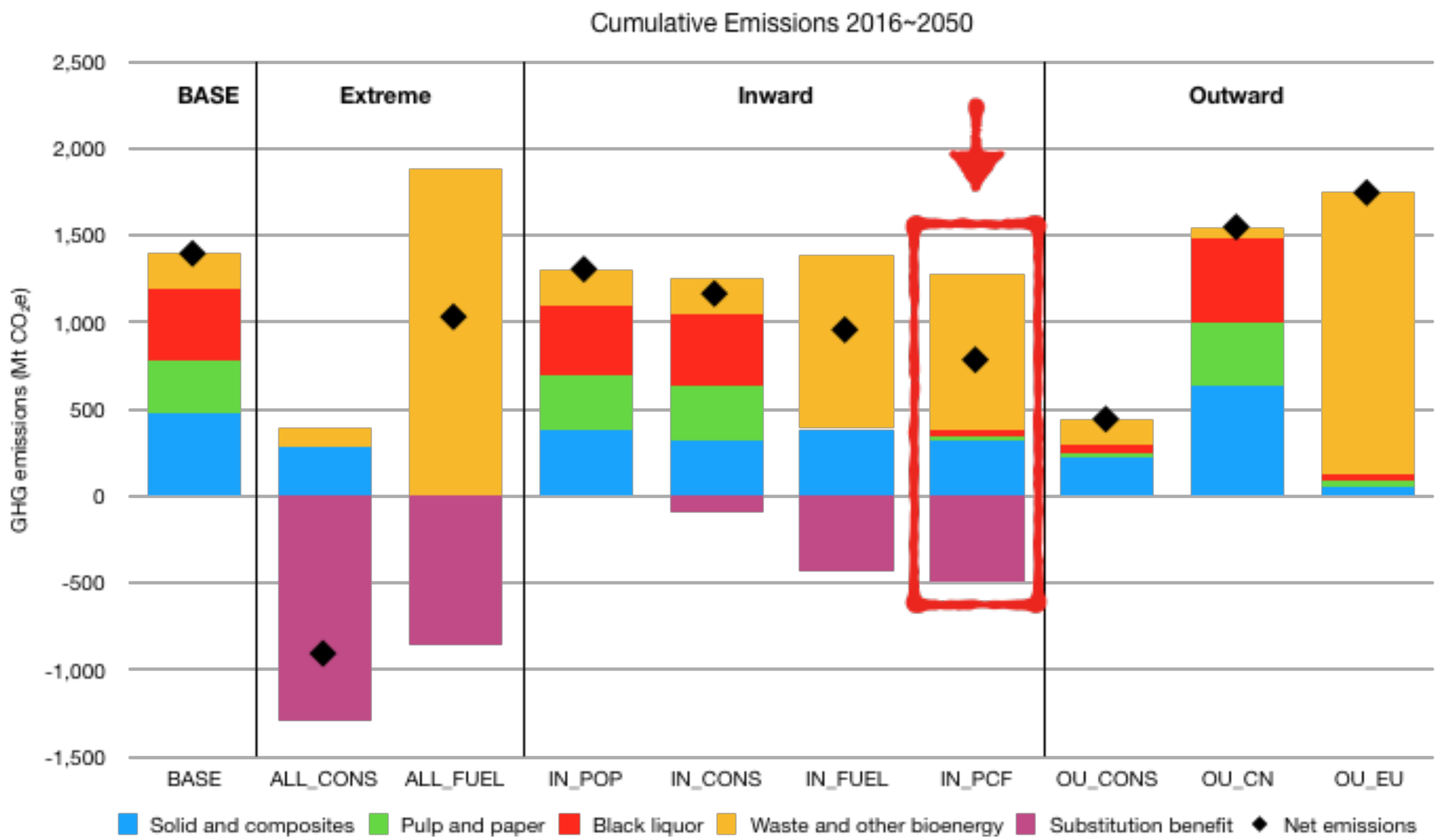

Figure 46. A comparison of the cumulative emission consequences from 2016 to 2050 of various scenarios including IN_PCF (positive values indicate increased emissions and negative values show the avoided emissions through substitution. Lower value means better). The avoided emissions results at 50th percentile are used to represent the substitution benefits.

Table 12. The cumulative (2016 to 2050) mitigation benefits by scenarios from BC's perspective (in $MtCO_2e$, higher value means better). The table is sorted by total mitigation benefit in descending order.

Scenarios	Storage benefit	Substitution benefit		Total mitigation benefit	
		Median	Range	Median	Range
ALL_CONS	1007	1296	561~1769	2303	1568~2776
OU_CONS	953	-	-	953	-
IN_PCF	**124**	**486**	**383~569**	**610**	**507~693**
IN_FUEL	4.7	434	368~496	439	373~501
ALL_FUEL	-486	851	722~971	365	236~485
IN_CONS	143	88	38~121	231	181~264
IN_POP	90	-	-	90	-
OU_CN	-152	-	-	-152	-
OU_EU	-350	-	-	-350	-

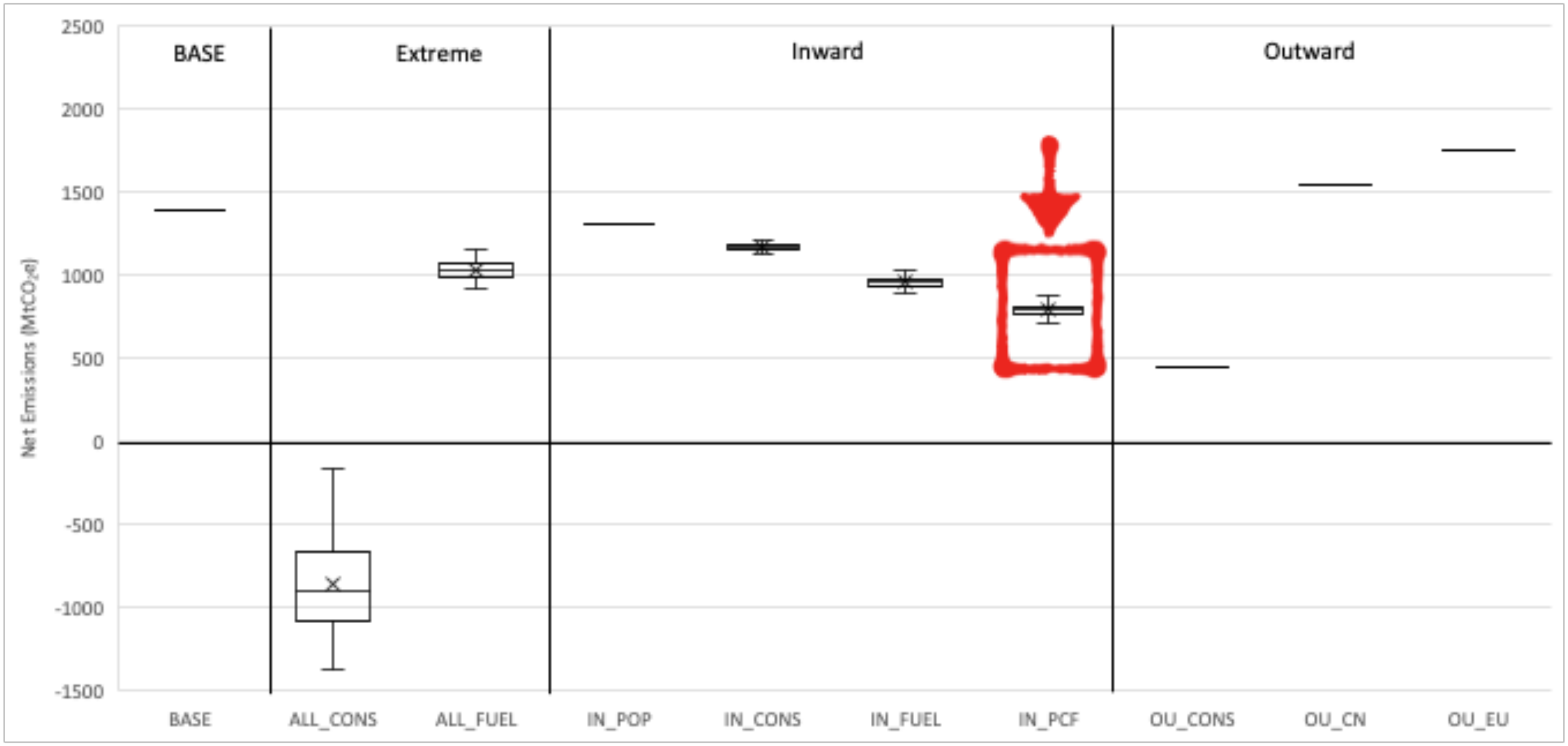

Figure 47. Box plots of the net cumulative emissions from 2016 to 2050 of various scenarios including IN_PCF (lower value means better). Uncertainty ranges are solely due to the displacement factor uncertainties (see Chapter 4) and other sources of uncertainty are not addressed.

The IN_PCF scenario ranked the third lowest net emissions among all scenarios and only resulted in higher net emissions than the ALL_CONS and OU_CONS scenarios (Fig. 46). The cumulative HWP emission reduction of 124 $MtCO_2$ (i.e., on average 3.5 $MtCO_2$ $year^{-1}$) between 2016 and 2050, but was 19 $MtCO_2e$ (i.e., on average 0.5 $MtCO_2e$ $year^{-1}$) less than the IN_CONS scenario Tbl. 12. This is because the IN_PCF scenario consumed the remaining biomass that was used for short-lived purposes abroad to produce biofuels and all of this biomass was treated as if it instantaneously oxidized. In the IN_CONS scenario, the material uses of this biomass were not released immediately. For example, paper and packaging product pools typically retain carbon for 2 years, and the uses of MDF and particleboard can typically retain carbon for 25 years. Black liquor emissions were greatly reduced in this scenario (red bars in Fig. 46) as paper production was limited to meet only the domestic demand (green bars in Fig. 46). Emissions from these two categories were the same as for the OU_CONS and OU_EU scenarios.

Cumulatively, the IN_PCF scenario produced a substitution benefit of approximately 486 $MtCO_2e$ (i.e., on average 13.9 $MtCO_2e$ $year^{-1}$) between 2016 and 2050. The net emissions of the IN_PCF scenario were 44% less than the BASE scenario and approximately midway between the IN_CONS and OU_CONS scenarios (Tbl. 12, Fig. 47). The total mitigation benefit was 610 $MtCO_2e$ compared to the BASE scenario (Tbl. 12), or an average of 17.4 $MtCO_2e$ $year^{-1}$ between 2016 and 2050, which is equivalent to about 30% of BC's 2050 GHG emission reduction target.

6.4 Discussion

The achievability of this construction-dominated and biofuel-subordinated bioeconomy is relatively high compared to the other extreme construction- or biofuel-focused scenarios. This strategy did not require building beyond feasible future market demand, but the domestic market share of timber construction needed to be doubled. This required the domestic timber construction floor area to increase from the present value of 3 million m^2 $year^{-1}$ to 7 million m^2 $year^{-1}$ [80–82, 134, 314]. The floor areas of timber construction in export markets (using BC wood) remained at the present value of 27 million m^2 $year^{-1}$. This strategy also produced 4.4 billion liters (L) $year^{-1}$ biofuel sourced from pulp logs and milling residues that are presently used to produce exported pulp and wood pellets. This volume was sufficient to displace the present fossil fuel demand in BC's heavy-load transportation, accounting for 50% of BC's total transportation fuel consumption [175]. If the light duty transportations can be electrified, this strategy may be a promising pathway for BC to achieve low carbon intensity in the transportation sector.

While such a massive restructuring of BC's economy would achieve greater mitigation benefits, the economic impacts would also be substantial. The pulp and paper industry has traditionally been very important to BC's financial and social prosperity, and in 2016 contributed 1.5 billion dollars to the province's GDP, employed 8 thousand people and supported several rural communities [79, 321–323]. The production facilities and market demand are yet to be developed for BC to convert from a traditional focus on the production and export of lumber and pulp to a construction-dominated-biofuel-subordinated self-sustaining domestic bioeconomy in order to improve GHG mitigations. In addition, as outlined in Ch. 1, the full commercial deployment of drop-in biofuels still faces major technical and economic challenges. However, BC's forest industry is currently experiencing large scale sawmill and pulp mill production curtailments and shutdowns caused by the reduction in timber supply and difficult market conditions [40, 41]. The growing global demand for the renewable bioproducts requires a structural transformation of BC's traditional forest industry and the wood products value-adding chain needs to be diversified and extended to increase BC's economic and social performance and competitiveness in international markets. Detailed socio-economic analysis would be needed to assess the feasibility of such a bioeconomy strategy.

It is also important to point out that this inward-focused construction- and biofuel-based bioeconomy examined in this study is a suboptimal solution from a global GHG emission perspective compared to an inward- and outward-combined construction-focused bioeconomy. As outlined in the introduction, the outward construction-focused bioeconomy is challenging to achieve due to constrained access to the foreign construction markets. However, if international consensus and collaboration on future wood buildings were in place, timber constructions have been demonstrated to be the most climate-efficient use of harvested biomass and BC has extensive infrastructure and knowledge on wood-frame constructions, which can potentially make the province a green building material advocate and increase the international market share in long-lived engineered wood products. In addition, although there are uncertainties around the technology, BC may want to focus its innovation towards the wood-based renewable fuels and to explore the possible transformation of uneconomical chemical pulp mills to biofuel production plants. As society's demand for chemically bleached pulp from BC has decreased more pulp mills may be closed in the future and opportunities for retooling some of this infrastructure to produce renewable liquid transportation fuels should be explored. Printing and writing paper is rapidly being replaced by digital media. Paper products for hygiene and packaging purposes are increasing to replace single use plastics but they may not all require to be produced from chemically bleached pulp and therefore black liquor emissions due to lignin removal may be reduced. The pulp to biofuel transformation may be able to rejuvenate rural communities and achieve both socio-economic benefits and contribute to clean energy targets.

6.5 Conclusion

An inward-focused construction- and biofuel-based harvested wood products bioeconomy achieved an average HWP emission reduction of 3.5 $MtCO_2e$ $year^{-1}$ between 2016 and 2050. Increasing the domestic market shares of timber construction to displace concrete and producing wood-based biofuels to displace fossil fuels in the domestic transportation sector was shown to be a better climate mitigation option than exporting HWPs for short-lived uses. The average substitution benefit was estimated to be approximately 13.7 $MtCO_2e$ $year^{-1}$ between 2016 and 2050 and the total mitigation benefit on average was 17.4 $MtCO_2e$ $year^{-1}$ which is 30% of BC's 2050 GHG emission reduction target.

From a global perspective, this inward-focused bioeconomy scenario is less climate-efficient than a construction-focused mitigation strategy. However, as a major HWP exporter, BC's influence on ensuring long-lived applications of its exported wood is limited. Although BC has extensive infrastructure and knowledge of green building methodology, obtaining the requisite access to foreign construction markets is uncertain and requires long-term effort. In the meantime, BC should advocate for increased timber construction both domestically and internationally and explore replacing the production of short-lived HWPs with the production of transportation biofuels for domestic consumption to meet legislated emission reduction targets.

7 CONCLUSIONS AND FUTURE WORK

7.1 CONCLUSIONS

This research demonstrated that BC could reduce GHG emissions by restructuring its forest bioeconomy, and quantified the comparative mitigation benefits of inward- versus outward-focused harvested wood products bioeconomy schemes, and material- versus energy-prioritized utilization strategies.

Between 1990 and 2016, emissions from wood products harvested in BC were cumulatively the largest component of BC's forest sector emissions and were consistently about 40 $MtCO_2e$ $year^{-1}$. Because BC is a major wood products exporter, 87% of these emissions were located in foreign markets. The internationally agreed production approach requires BC to report emissions from wood harvested in BC, regardless of where in the world the HWP emission occur. Longer carbon storage times in HWPs, such as increased structural uses, are required to reduce HWP emissions. Substitution effects of HWPs can reduce emissions from the transportation and building sectors which are consistently the highest emitters in BC, accounting for 25 $MtCO_2e$ $year^{-1}$ and 8 $MtCO_2e$ $year^{-1}$ respectively in 2016. The demand for woody biomass has been projected to increase as many sectors seek to reduce their carbon intensity. However, BC's roundwood harvest has been forecast to decline in the coming decades and therefore BC's harvest may not be able to meet the future demand for fiber.

Modeling the production, consumption, recycling and disposal of HWPs by society is complex and therefore a model is required to estimate HWPs carbon dynamics. The existing Canadian harvested wood product carbon dynamics model was designed for reporting purposes and the structure has been developed for efficiency based on the available historical HWP production and consumption data. It has limitations as a tool for mitigation analysis. A refined model, MitigAna, was developed to enable scenario-based mitigation analyses from the demand side with additional modules that quantified substitution benefits and postconsumer cascades. The MitigAna model also improved the carbon dynamics by defining the HWP carbon flows in explicit stages including detailed residue allocations and end-use applications. This overcame the issue of oversimplification noted in previous HWP models. The model was equipped with biomass flow barriers that reflected the biomass utilization hierarchies in the wood industry and addressed the distinct raw material requirements for different HWP commodities and end-uses. This hierarchical concept enabled the biomass supply to shift according to the different specifications of the trade and utilization scenarios. The MitigAna model also introduced a new approach to model the increasingly important residential renovation component to avoid the overestimation of carbon storage benefits. This model used cumulative Gamma distributions to better estimate the carbon retention patterns of various HWP end-uses and updated the HWP end-use service lives according to our previous research findings.

Using the MitigAna model, major emission sources and potential reduction contributors in the wood products sector were identified and quantified. The required market size for each scenario was estimated. Strategically, construction is the most climatically efficient application of wood products because it provides long-term storage of carbon and its substitution effect reduces the emissions from other sectors. However, BC does not currently have sufficient market access or manufacturing capacity to fully realize the mitigation potential of a strategy that maximizes structural applications, unless international consensus and collaboration on constructing future buildings with wood are in place. North America and Nordic countries are pursuing timber buildings which consume a substantial amount of wood, but other important markets (e.g., China) are relying heavily on concrete and steel construction methods. An uncertainty analysis of displacement factors demonstrated that in 98% of circumstances, using wood buildings to displace concrete buildings would provide higher substitution benefits than using wood-based transportation fuels to replace fossil fuels per unit of wood use (i.e., larger displacement factor). However, market size is an important factor in determining the scale of the substitution benefits and this was demonstrated by the observation that the biofuel displacement market in BC is large enough to outweigh the substitution benefit of biofuels over the combined storage and substitution benefits of construction. This study revealed that if exported HWPs are not used in applications with an average service life of more than 32 years, then an inward-focused biofuel strategy would be more beneficial than an export-oriented HWP strategy from the perspective of domestic GHG balances. Currently, the service lives of BC wood exported to China (with a mass-based average of 5.7 years) and Europe (with a mass-based average of 0 years) are significantly lower than this threshold. From the sole perspective of unilateral GHG emission reduction targets, BC would be better off by shifting biomass supply from short-lived exports, such as pulp and wood pellets, to biofuel production and mandating that these biofuels displace fossil fuels in Canada. However, such use of BC wood products would not yield the greatest possible global climate change mitigation benefit. Thus, increased efforts to inform BC trading partners of the benefits of mass-timber building and other long-lived wood products uses may both expand BC market opportunities and increase global climate change mitigation benefits.

Extending the service life of BC's harvested biomass through cascading uses in Canada, US and Japan only provided marginal carbon storage benefits with a reduction of 1.16 $MtCO_2e$ $year^{-1}$ on average between 1990 and 2050. Increasing the recycling rate from 30% to 85% yielded only a 2.2% further reduction in total emissions and revealed that a diminishing rate of return exists for the cascading uses of wood. The ongoing development of cascading technology indicated great uncertainties in emissions arising during the collecting, sorting and remanufacturing processes. BC may wish to implement a simple and cost-effective wood cascading system instead of pursuing technology and infrastructure to optimize wood recycling rates because greater mitigation benefits would be achieved through focusing on restricting wood exports for short-lived uses. Especially notable targets for short-lived applications are kraft pulping products, as black liquor accounted for about 30% of the total HWP emissions, and wood pellets exported to the EU that accounted for about 10%. These emissions are substantially larger than the upper-bound climate benefit that cascading uses of wood can achieve.

This study evaluated a vision for BC's forest sector that combined mass-timber construction and transportation biofuels under conditions that maximized GHG mitigation and ignored socio-economic constraints. This combined strategy achieved an average reduction of 17.4 $MtCO_2e$ $year^{-1}$ between 2016 and 2050, which is equivalent to about 30% of BC's 2050 GHG emission reduction targets. The achievability of this combined strategy is relatively high compared to the other extreme construction- or biofuel-focused scenarios. This strategy did not require building beyond feasible future market demand. It required the domestic market share of wood construction to be approximately doubled. This combined strategy produced sufficient wood products to construct a domestic floor area of 7 million m^2 $year^{-1}$ compared to the present value of 3 million m^2 $year^{-1}$ [80–82, 134, 314]. The floor areas of foreign timber construction (using BC wood) remained the present value of 27 million m^2 $year^{-1}$. This strategy also produced 4.4 billion L $year^{-1}$ biofuel sourced from pulp logs and milling residues that are presently used to produce exported pulp and wood pellets. This volume was sufficient to displace the present fossil fuel demand in BC's heavy-load transportation, accounting for 50% of BC's total transportation fuel consumption [175]. If light duty transportations can be electrified, this strategy may be a promising pathway for BC to achieve low fossil carbon intensity in the transportation sector. There are uncertainties around the wood-based biofuel production technology, which is not yet commercially viable at a scale that is comparable to the conventional fuels. However, this study has highlighted that the possible transformation of chemical pulp facilities to biofuel production plants may provide an outcome of improved mitigation that could also aid the rejuvenation of the rural communities. It can also extend the value-adding production chain by taking the output of the well-established wood pellets facilities. Therefore, there are substantial GHG benefits and likely socio-economic benefits to be attained by BC investing in innovations associated with commercializing the wood-to-drop-in biofuel technologies.

However, it is important to point out the potential conflict between BC-specific benefits and maximizing the global GHG mitigation outcome. If international collaborations on future wood buildings were in place, BC's harvested wood products sector could make a maximum global mitigation contribution of 66 $MtCO_2e$ $year^{-1}$. As noted above, without these agreements being in place and using the production approach, it is advantageous to BC's GHG mitigation to use a hybrid strategy that combines wood construction and biofuel production. By using less biomass for long-lived high displacement applications, the world achieves less GHG mitigation per unit of roundwood harvested in BC. The development of a construction-focused bioeconomy would need more engineered wood products to be created for the construction sector, which means that more finger-jointing facilities, cross-laminated timber plants and other value-added facilities would need to be built in BC. The technology to manufacture engineered wood products is relatively mature, the risk is lower and the required capital investment will be lower than building biofuel plants. These value-added downstream facilities can create jobs, in addition to the existing lumber- and pulp-dominated bioeconomy structure in BC. This analysis highlights the far-reaching consequences of international GHG accounting rules for HWP and the need to align them with the desired global outcomes.

In summary, this thesis quantified the mitigation benefits of timber construction, wood-based biofuels and cascading uses of wood under inward- and outward-focused utilization scenarios and proposed a vision for BC's wood products sector to build a bioeconomy that can contribute to the province's greenhouse gas emission reduction targets. The outcome of this research can be used to evaluate the effectiveness of BC's mitigation policies and inform decisions for the policy community and investment groups. It can be used to identify important issues in our mitigation strategies by comparing the projected mitigation benefits with the reported outcomes and aid progressive development of those strategies. It provides a quantitative basis for future socio-economic analyses that evaluate the consequences of the proposed strategy to society and to the economy of the province and eventually implement effective climate actions.

7.2 Limitations

This research quantitatively compared various harvested wood products mitigation strategies from a carbon perspective with consideration of market size and access. The goal is to be descriptive rather than prescriptive. Although the overall conclusions are believed to be wide applicable, there are some limitations of this study.

The challenges of accurately quantifying the substitution benefit of wood products are due to the lack of context-specific data and information, such as geographical locations, building designs, future technological advancements that alter the emissions-intensity of timber and non-timber products and whether material or fuel switching will result in substitution or contribute to energy rebound (i.e., increased demand following price reduction triggered by reduced demand from substitution) or leakage (i.e., substituted materials are used elsewhere). The results in this research are limited by the data that are available to us. The estimation was conducted from a BC-centric viewpoint and while it examined global carbon storage in HWP products from BC harvested wood, the substitution benefit analysis was limited to domestic product uses. Thus, greater substitution could be achieved at the global level from exported HWP but that was not examined in detail.

In terms of the uncertainty analysis of substitution benefits conducted in this research, we are fully aware that technology advancing and as more data become available, these could widen or narrow the displacement factor uncertainty ranges in the future. Technological improvements in other sectors (e.g., concrete industry and hydrogen fuel cells) will also increase or decrease the values of the displacement factor and may even affect the validity of harvested wood products' substitution benefits. The target of the uncertainty analysis was the impact of model parameters on substitution benefits of construction and biofuel under various scenarios. In other words, this analysis did not quantify the probabilities or uncertainties of the entire scenarios.

BC's current forest industry production mix is dominated by lumber, pulp and wood pellets. This research proposed to extend and diversify the existing value-added chain. Scenarios in this research accomplished this proposition by putting relatively more weight on two main end uses, timber construction and wood-derived transportation biofuel as outlined in the CleanBC plan. Other mitigation options of conventional technologies, such as wood pellets replacing coal in Alberta and Ontario or natural gas in district heating and mechanical pulp substituting for chemical pulp, were not examined. In reality, the future structure of BC's wood-based bioeconomy will likely be a dynamic mix of conventional and novel technologies.

The assessment of the mitigation strategies developed in this research was limited to the magnitudes of emission reduction benefits and market access. Developing viable mitigation solutions will also require comprehensive socioeconomic impact analyses for BC's forest sector.

7.3 FUTURE WORK

7.3.1 *MODEL IMPROVEMENTS*

At this stage, the MitigAna model does not have a completed landfill module. The carbon dynamics of HWP within landfills are rather uncertain but given the importance of this end-of-life phase, it should be modeled. This area will be one of the topics of our future work.

Fossil fuel emissions associated with the production and transportation of wood products are important for estimating the substitution benefits of various HWP end-uses. Currently the substitution benefits are normally calculated on an extended module using displacement factors determined from the results of life cycle assessments. Presently, the main component of the MitigAna model only considers biogenic emissions. Integrating the fossil emission assessments directly into the model is possible [263, 362] and would expand the scope and accuracy of the estimated climate impact of the modeled mitigation strategy.

7.3.2 *FUTURE BIOMASS PROVISION AND RESIDUE UTILIZATIONS*

The provincial action plan outlined in the CleanBC strategy will result in an increasing demand for woody biomass for mass timber construction and renewable transportation fuel production. The demand for wood pellets produced in BC to replace fossil fuels in heat and power generation in Europe continues to rise. In this research, the future harvest was held at the base scenario. There could be further opportunities to increase the harvest volume if forest management was intensified through measures such as thinning and fertilization. On the other hand, BC has experienced several severe wildfire seasons since 2003. Questions have been raised on rehabilitation strategies and solutions to reduce the risk of fires. For example, can some of the efforts and resources spent on fuel reduction treatment such as prescribed burning be reallocated towards biomass collection and utilization? Can BC's harvest strategies include post-fire salvage logging? The source of biomass provision may shift significantly in the coming decades in terms of both volume and quality. It is therefore important to have an improved understanding of its availability and the techno-economical boundaries and GHG consequences of biomass utilization.

7.3.3 *SOCIO-ECONOMIC ANALYSIS AND POLICY DEVELOPMENT*

This work has shown that achieving BC's GHG emission reduction target would require changing the structure of BC's forest bioeconomy. One option to facilitate this change is through a hierarchical carbon incentive or price system. The existing carbon incentive programs vary by region, but a general concept is that the program audits the GHG reduction achieved by a plant and grants incentives that are equivalent to that reduction. The analyses undertaken in this thesis have shown that the different uses of wood products result in divergent emission consequences from the same biomass input. The incentive system may therefore need to consider the amount as well as the quality of biomass a plant has consumed to achieve such reductions. Developing such a system would require detailed GHG modeling, comprehensive socioeconomic analysis, and careful planning.

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APPENDICES

APPENDIX A FLOW ANALYSIS

Fig. 48 is a volumetric flow analysis of BC's harvested wood products supply chain up to the commodity level. The unit in Fig. 48 is thousand cubic meters roundwood equivalent under bark (000 m^3 rwe u.b.). The flow starts from the left upper corner with 67,826,000 m^3 rwe u.b. harvested from BC's forest in 2016. The green color indicates that the physical state of the biomass is roundwood. Roundwood were consumed to produce sawnwood, plywood, OSB, pulp and by-products. The light blue column indicates the primary product outputs from various types of mills. The export of these primary products are not shown in this table. The light orange column indicates the wood chip outputs from mills. Wood chips (23,934,000 m^3 rwe u.b.) were allocated to pulp and paper mills. The yellow column indicates the sawdust outputs from mills. Sawdust was allocated to pulp and paper mill, MDF mills and wood pellet mills. Sawdust may be consumed onsite of the mills as bioenergy, however high resolution mill-specific data were not always available (wood fuel use in MDF and OSB mills were estimated from LCA studies). Fig. 48 shows the bioenergy use of sawdust as an individual category. Energy uses were collected in the orange column. Light green and blue column indicate the production volume of chemical (10,111,000 m^3 rwe u.b.) and mechanical pulp (1,250,000 m^3 rwe u.b.). Only a fraction of the pulp produced were consumed for paper manufacturing in BC (2,691,000 m^3 rwe u.b. and 813,000 m^3 rwe u.b.), and the rest was exported.

Fig. 49 is a Sankey diagram of carbon flow of BC's harvested wood products supply chain in 2016. It is plotted using the output data of the MitigAna model.

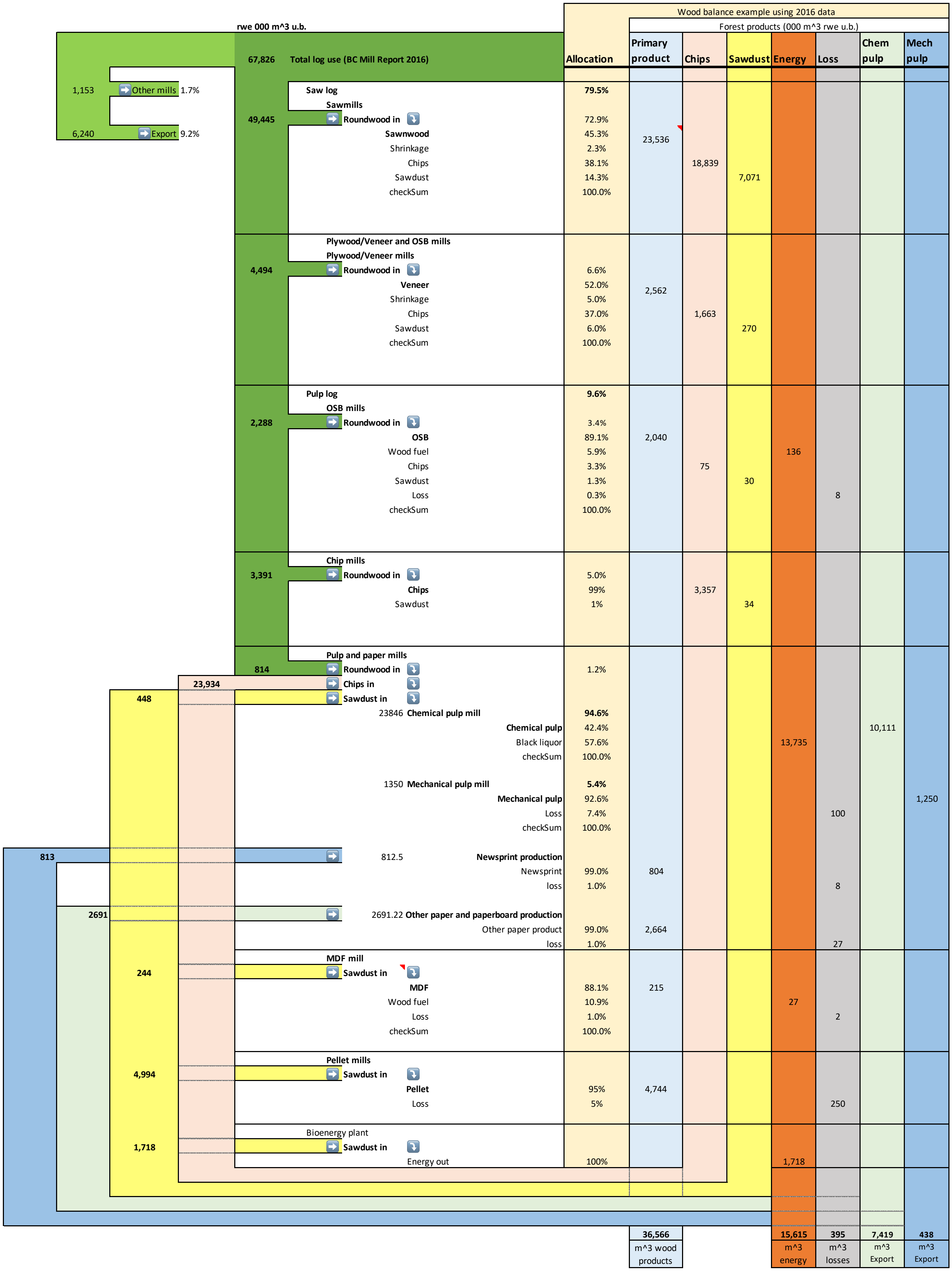

Figure 48. BC woody biomass flow, production and yield.

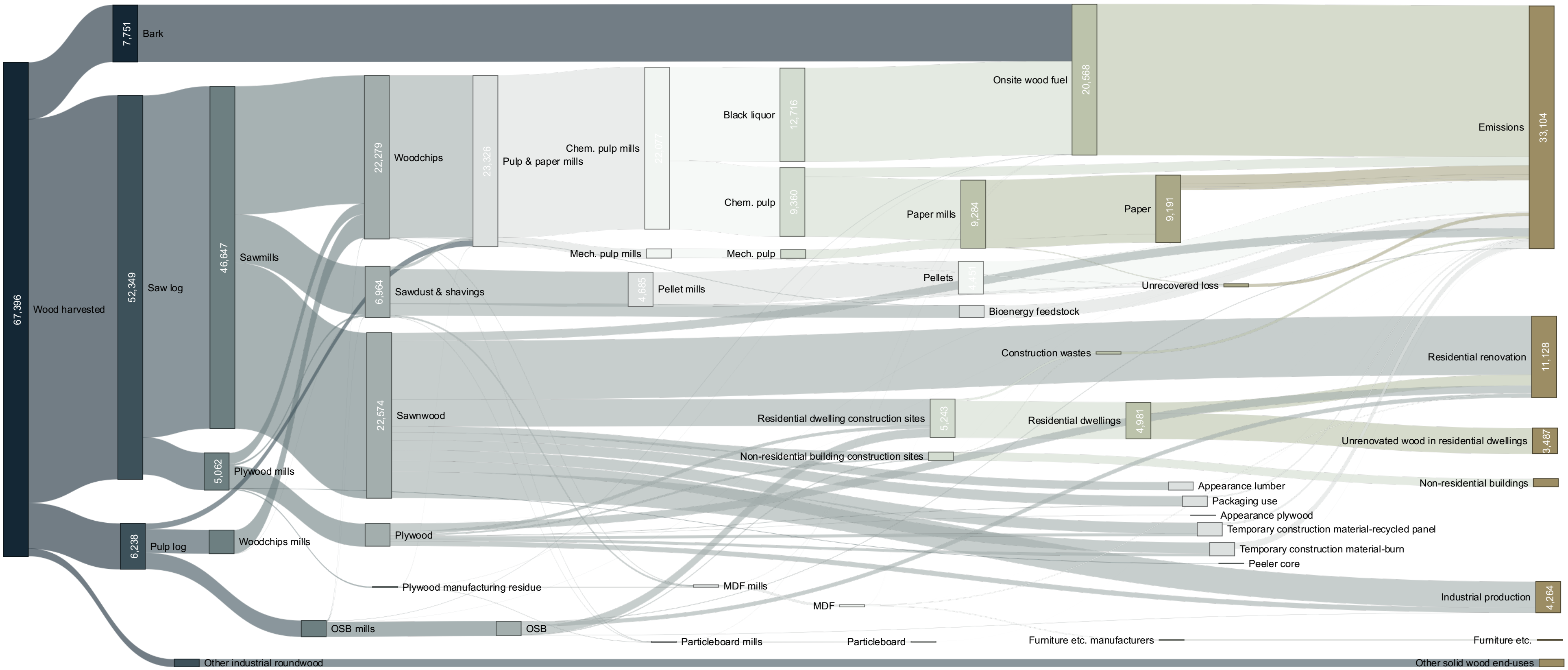

Figure 49. A Sankey diagram of MitigAna output of 2016 flux in supply chain without geo locations. Unit: ktCO$_2$e year^{-1}.

Appendix B Brock Commons Calculation

Description	Value	Unit	Reference
Carbon content of wood	0.5	tC (t wood)$^{-1}$	[313]
CLT and Glulam (Douglas fir) density	0.470	t m^{-3}	[313]
Volume of wood products used in Brock Commons (CLT and GluLam combined)	2233	m^{3}	[312]
Average annual sawnwood products sent to residential dwellings in the ALL_CONS scenario	5,340,841	tC year^{-1}	This study
	10,681,682	t wood year^{-1}	
	22,726,984	m^{3} year^{-1}	
Average annual number of residential buildings required to be built under the ALL_CONS scenario relative to Brock Commons (bce) in terms of structural wood consumption	10,178	bce year^{-1}	
Average annual sawnwood products sent to residential dwellings in the OU_CONS scenario	4,865,773	tC year^{-1}	This study
	9,731,546	t wood year^{-1}	
	20,705,417	m^{3} year^{-1}	
Average annual number of residential buildings required to be built under the OU_CONS scenario relative to Brock Commons (bce) in terms of structural wood consumption	9,272	bce year^{-1}	

bce: Brock Commons equivalent.

Appendix C Renewable Transportation Fuel Calculation

Renewable Fuel Yield Calculation - Pyrolysis Pathway

Pyrolysis Pathway	Parameter name	Value	Unit	Reference	Notes
Data from the literature	Pyrolysis plant yield	1.65	kg forest residue input (L bio-oil output)$^{-1}$	[185]	bio-oil is the intermediate product that needs to be upgraded to the final fuel
	Bio-oil density	1200	g L^{-1}	[193, 318, 364]	
	Upgrading plant yield	2.14	kg bio-oil input (L final fuel output)$^{-1}$	[185]	
	S-P-F Density	378	kg m^{-3}	[365]	
Calculations	Pyrolysis plant yield unit conversion	1.38	kg forest residue input (kg bio-oil output)$^{-1}$		Pyrolysis plant yield / (bio-oil density / 1000), bio-oil not final fuel
	Overall yield	2.94	kg forest residue input (L final fuel output)$^{-1}$		Pyrolysis plant yield unit conversion * upgrading plant yield
	Overall yield conversion	128.46	L final fuel output (m^{-3} wood input)		S-P-F Density / Overall yield

Renewable Fuel Yield Calculation - Hydrothermal Liquefaction (HTL) Pathway

HTL Pathway	Parameter name	Value	Unit	Reference	Notes
Data from the literature	Forest residue to bio-oil	0.37	kg bio-oil output (kg forest residue input)$^{-1}$	[193]	Converting from forest residue to intermediate bio-oil
	Forest residue to wood pellet	0.89	kg wood pellet output (kg forest residue input)$^{-1}$	[189]	Converting from forest residue to wood pellet
	Wood pellet to bio-oil	0.37	kg bio-oil output (kg wood pellet input)$^{-1}$	[193]	Converting from wood pellet to intermediate bio-oil
	Bio-oil to final oil	0.75	weight%	[193]	
	S-P-F Density	378	kg m^{-3}	[365]	
	Final fuel density	826.00	kg m^{-3}	[197]	This is a blended value of renewable gasoline, jet fuel, Diesel and by-product heavy oil
Calculations	Forest residue to final fuel yield	0.28	kg final fuel output (kg forest residue input)$^{-1}$		Not convert to wood pellet first for transportation
	Forest residue to wood pellet, then final fuel yield	0.24	kg final fuel output (kg forest residue input)$^{-1}$		Convert to wood pellet first for transportation
	Forest residue to final fuel yield conversion	125.96	L final fuel output (m^{-3} wood input)		Not convert to wood pellet first for transportation
	Forest residue to wood pellet, then final fuel yield conversion	112.11	L final fuel output (m^{-3} wood input)		Convert to wood pellet first for transportation

Renewable fuel meeting energy demand of BC's transportation sector

	Parameter name	Value	Unit	Value	Unit	Reference	Notes
Data available	HHV of renewable fuel	35.57	MJ L^{-1}			[193, 318, 364]	
	Yield	122.18	L final fuel output (m^{-3} of wood input)				Average of pyrolysis and HTL yield
	Bioenergy feedstock in IN_FUEL scenario	27,479,862	tCO_2e $year^{-1}$				Taken from inward-focused, renewable fuel scenario. All pulp log and milling residue are sent to bioenergy feedstock, all time average
	Bioenergy feedstock in ALL_FUEL scenario	53,827,483	tCO_2e $year^{-1}$				Taken from all harvest to renewable fuel scenario. All the harvest is sent to bioenergy feedstock, all time average
	Bioenergy feedstock in IN_PCF scenario	25,301,614	tCO_2e $year^{-1}$				Taken from inward construction-dominated biofuel subordinated scenario, all time average
	BC's transportation demand	334.45	PJ			[317]	
	S-P-F Density	378.00	kg m^{-3}			[365]	
	Wood carbon content	0.51				[193, 318, 364]	
Calculations	Yield conversion	6.15	MJ final fuel output (kg CO_2e of wood input)$^{-1}$				
	Renewable fuel output of IN_FUEL scenario	168.95	PJ $year^{-1}$	4749.74	Million L $year^{-1}$		

	Renewable fuel output of ALL_FUEL scenario	330.94	PJ $year^{-1}$	9303.77	Million L $year^{-1}$		
	Renewable fuel output of IN_PCF scenario	155.56	PJ $year^{-1}$	4373.24	Million L $year^{-1}$		
	BC coverage of IN_FUEL scenario	51%					
	BC coverage of ALL_FUEL scenario	99%					
	BC coverage of IN_PCF scenario	47%					

Appendix D Building DF Calculation

DFs calculated based on multi-unit residential building benchmarking [337]

	Brock Commons	Ponderosa Commons	Difference	DF calculation	Unit
GHG emissions	250	348	98		**kgCO_2e m^{-2}**
Floor area	15,115	12,838			**m^2**
Wood use	57.07	2.85	54.22		**kg wood m^{-2}**
Carbon in wood	105.44	5.23	100.20		**kg CO_2e m^{-2}**
DF				1.81	**t CO_2e (t wood)$^{-1}$**
DF				0.98	**t CO_2e avoided (t CO_2e in wood)$^{-1}$**

DFs calculated based on Brock Commons and Ponderosa Commons environmental building declarations (EBD) [157, 313, 283, 366]

	Brock Commons	Ponderosa Commons	Difference	DF calculation	Unit
EBD emissions per floor area	1978.29	2005.68	27.38		**kg CO_2e m^{-2}**
Embodied emissions per floor area	314.74	418.36	103.62		**kg CO_2e m^{-2}**
Wood use	57.06	2.85	54.20		**kg wood m^{-2}**
Carbon in wood	105.40	5.23	100.17		**kg CO_2e m^{-2}**
EBD DF				0.51	**t CO_2e (t wood)$^{-1}$**
EBD DF				0.27	**t CO_2e avoided (t CO_2e in wood)$^{-1}$**
Embodied DF				1.91	**t CO_2e (t wood)$^{-1}$**
Embodied DF				1.03	**t CO_2e avoided (t CO_2e in wood)$^{-1}$**

DFs calculated based on Wood Innovation and Design Center whole building LCA [123]

	Value	Unit	Comment
Difference in wood use	568.23	**t wood**	
Difference in wood use	286.23	**tC in wood**	
Diff emissions	1.29e+03	**tCO_2e**	
Diff emissions	3.50e+02	**tC**	
DF	2.26	**tCO_2e avoided (t wood)$^{-1}$**	Both embodied and operational. Assuming operational energy is the same for both buildings.
DF	1.22	**tC avoided (tC wood use)$^{-1}$**	Both embodied and operational. Assuming operational energy is the same for both buildings.

DFs calculated based on multi-story CLT office building in Burnaby, BC [107]

	Value	Unit
Floor area	14,233	m^2
Timber Construction - Wood use	3,131	tCO_2e
Timber Construction - Emissions	126	kg CO_2e m^{-2}
Concrete Construction - Emissions	420	kg CO_2e m^{-2}
Concrete Construction - Avoided Emissions	4,185	tCO_2e
DF	1.34	tCO_2e avoided (tCO_2e additional wood use)$^{-1}$

DFs calculated based on Australia light-frame wood construction compare to concrete, real building LCA [115]

	Light-frame multi-storey	Concrete	Unit
Floor area	3895	5912	m^2
Height	5	8	
Wood use	233,240	0	kg
Wood use	110	0	$kgCO_2e\ m^{-2}$
Emissions (embodied)	382.1	489.7	$kgCO_2e\ m^{-2}$
Emissions (whole)	4062.8	4152.4	$kgCO_2e\ m^{-2}$
DF - embodied	0.98		
DF - whole	0.82		

DFs calculated based on New Zealand LVL light-frame wood construction [124]

Floor area	4247	m^2				
height	6	Storey				
	Wood use	**Unit**	**Embodied - Emission**	**Unit**	**Whole building**	**Unit**
Concrete	32.38	tCO_2e	1884	tCO_2e	6794	tCO_2e
Steel	31.22	tCO_2e	1883	tCO_2e	6883	tCO_2e
Timber	846.4	tCO_2e	821	tCO_2e	5982	tCO_2e
Timber+	1162.28	tCO_2e	238	tCO_2e	5276	tCO_2e
	Embodied	**Whole**	**Unit**			
DF - timber vs concrete	1.31	1.00	tCO_2e avoided (tCO_2e additional wood use)$^{-1}$			
DF - timber+ vs concrete	1.46	1.34	tCO_2e avoided (tCO_2e additional wood use)$^{-1}$			
DF - timber vs steel	1.30	1.11	tCO_2e avoided (tCO_2e additional wood use)$^{-1}$			
DF - timber+ vs steel	1.45	1.42	tCO_2e avoided (tCO_2e additional wood use)$^{-1}$			

DFs calculated based on selected studies

	tCO_2e avoided	t wood in wood-frame	t wood in concrete-steel frame	tCO_2e in additional wood	DF (tCO_2e avoided (tCO_2e in additional wood)$^{-1}$)	Comment
Lippke et al. 2004 [339]	22.8	13	6.5	11.9	**1.9**	
Sathre et al. 2010 [30]					2.1	
Gustavsson et al. 2006 [170]	121.1	98	70	51.3	**2.4**	Sweden and Finland low-rise wood frame, compare to fictitious functional equivalent concrete buildings
Scheuer et al. 2003 and Smyth et al. 2016 [110]	503	113	3	201.7	**2.5**	Sam Wyly Hall in University of Michigan. Steel and concrete 6 storey multi-use, compare to fictitious scenario if built with wood, steel or concrete.

APPENDIX E PYROLYSIS DF CALCULATION

Conversion factors [185, 193, 318]

Item	Para	Val	Unit
Wood Residue	Carbon Content	51%	
Bio-oil	HHV	21	MJ L^{-1}
	Density	1200	g L^{-1}
Refined Bio-oil	HHV	46.1	MJ kg^{-1}
	HHV	35.57	MJ L^{-1}
	Density	772	g L^{-1}
	Jet fraction (mass)	13.75%	
	Diesel fraction (mass)	41.25%	
	Gasoline fraction (mass)	45%	
Diesel	HHV	45.8	MJ kg^{-1}
	HHV	38.65	MJ L^{-1}
	Density	843.2	g L^{-1}
Gasoline	HHV	46.9	MJ kg^{-1}
	HHV	34.69	MJ L^{-1}
	Density	739.2	g L^{-1}
Jet A-1	HHV	46.3	MJ kg^{-1}
	HHV	37.4	MJ L^{-1}
	Density	808	g L^{-1}

Yield of bio-oil and wood-based "drop-in" biofuel [185]

	Value	Unit
Bio-oil yield	1.65	kg wood (L bio-oil)$^{-1}$
Final fuel yield	2.14	kg bio-oil (L final fuel)$^{-1}$

Pyrolysis LCA results [185]

Scenarios	GWP (gCO_2e MJ^{-1})
Scenario 1	25.7
Scenario 2	26.1
Sceanrio 3	28.3

Fossil fuel embodied emissions

Fuel types	Value	Unit
2005 gasoline baseline [185]	93	gCO2e MJ^{-1}
Conventional jet fuel baseline [208]	87.5	gCO2e MJ^{-1}
Conventional diesel baseline [209–211]	93	gCO2e MJ^{-1}

Pyrolysis DF Calculation

	Scenario 1	Scenario 2	Scenario 3	Unit
Intermediate oil	1	1	1	L bio-oil
	1.2	1.2	1.2	Kg bio-oil
Output final oil	0.56	0.56	0.56	L final fuel
	19.95	19.95	19.95	MJ final fuel
Input wood	1.65	1.65	1.65	Kg wood input
	0.84	0.84	0.84	Kg C wood input
	0.04	0.04	0.04	Kg C wood (MJ final fuel)$^{-1}$
Jet fuel DF	0.06	0.06	0.06	KgCO2e avoided MJ^{-1}
	0.02	0.02	0.02	KgC avoided MJ^{-1}
	0.40	0.40	0.38	kgC avoided (kgC wood)$^{-1}$
Renewable diesel DF	0.07	0.07	0.06	KgCO2e avoided MJ^{-1}
	0.02	0.02	0.02	KgC avoided MJ^{-1}
	0.43	0.43	0.42	kgC avoided (kgC wood)$^{-1}$
Renewable gasoline DF	0.07	0.07	0.06	KgCO2e avoided MJ^{-1}
	0.02	0.02	0.02	KgC avoided MJ^{-1}
	0.43	0.43	0.42	kgC avoided (kgC wood)$^{-1}$

Additional pyrolysis DF calculations based on Ontario facilities producing for California

Fuel Producer: Ensyn Technologies Inc.

Facility Name: Ensyn Ontario Facility.

Renewable transportation fuel from forest residues via pyrolysis and co-processing of bio oil.

DF calculations based on Ontario facilities producing for California [180]

Fuel Category	Transportation	Facility Location	Feedstock	GWP (gCO2e/MJ)	DF
Renewable Gasoline	Rail	Ontario	Pyrolysis from Forest Residue	21.17	0.46
Renewable Gasoline	Truck	Ontario	Pyrolysis from Forest Residue	26.08	0.43
Renewable Diesel	Rail	Ontario	Pyrolysis from Forest Residue	22.42	0.46
Renewable Diesel	Truck	Ontario	Pyrolysis from Forest Residue	27.33	0.42

APPENDIX F HYDROTHERMAL LIQUEFACTION DF CALCULATION

Conversion factors [197]

Parameters	Value	Unit
Annual productivity of total biofuels	100	Million L
Forest residues to bio-oil	0.367	kg bio-oil (kg dry forest residues)$^{-1}$
Forest residues to wood pellet	0.89	kg wood pellet (kg dry forest residues)$^{-1}$
Wood pellet to bio-oil	0.367	kg bio-oil (kg dry wood pellet)$^{-1}$
Bio-oil to deoxygenated oil	75	weight%
Wood pellet moisture content	5.6	weight%
Biofuels products distribution		
Gasoline proportion [341]	21	weight%
Jet fuel proportion [341]	25	weight%
Diesel proportion [341]	35	weight%
Heavy oil proportion [341]	19	weight%
Biofuels density		
Gasoline density [193]	739	kg m^{-3}
Jet fuel density [193]	808	kg m^{-3}
Diesel density [193]	843	kg m^{-3}
Heavy oil density [193]	944	kg m^{-3}

HTL LCA results [197]

Scenarios	GWP (gCO2e MJ^{-1})
Fr-CIR	13.69
Bo-DBR	10.21
Wp-CIR	12.67

HTL DF Calculation

	Scenario 1	Scenario 2	Scenario 3	Unit
Output	3.56e+09	3.56e+09	3.56e+09	MJ biofuel produced
Input	51.24	43.05	43.05	gC wood used (MJ biofuel production)$^{-1}$
Jet fuel	20.41	20.13	21.08	gC avoided (MJ jet fuel)$^{-1}$
	0.40	0.47	0.49	gC avoided (gC wood)$^{-1}$
Diesel	21.9	21.6	22.6	gC avoided (MJ jet fuel)$^{-1}$
	0.43	0.50	0.52	gC avoided (gC wood)$^{-1}$
Gasoline	21.9	21.6	22.6	gC avoided (MJ jet fuel)$^{-1}$
	0.43	0.50	0.52	gC avoided (gC wood)$^{-1}$