Life cycle analysis of forest-based biomass at the Atikokan power plant

A full life cycle analysis and framework development of Ontario-sourced forest biomass for electricity and heat generation

DRAFT FINAL REPORT

Dave Lovekin • Rich Wong

Tej Gidda • Monica Radulescu • Tanya Bogoslowski

Barry Wilson • Chad Ellis • Sean Sharpe

March 2012

the PEMBINA institute

Sustainable Energy Solutions

Life cycle analysis of forest-based biomass at the Atikokan power plant – FINAL REPORT – DRAFT
March 2012

Disclaimer

This document is an independent report prepared exclusively as information for Environment Canada.

The views and opinions expressed in this report are those of the author(s).

The information, statements, statistics and commentary (together the 'information') contained in this report have been prepared by the Pembina Institute from publicly available material, information gathered through the research efforts and joint subprojects and from discussions held with stakeholders. The Pembina Institute does not express an opinion as to the accuracy or completeness of the information provided, the assumptions made by the parties that provided the information or any conclusions reached by those parties.

The Pembina Institute have based this report on information received or obtained, on the basis that such information is accurate and, where it is represented to The Pembina Institute as such, complete.

About the Pembina Institute and Pembina Consulting

The Pembina Institute is a national non-profit think tank that advances sustainable energy solutions through research, education, consulting and advocacy. It promotes environmental, social and economic sustainability in the public interest by developing practical solutions for communities, individuals, governments and businesses. The Pembina Institute provides policy research leadership and education on climate change, energy issues, green economics, energy efficiency and conservation, renewable energy, and environmental governance. For more information about the Pembina Institute, visit www.pembina.org or contact info@pembina.org.

The Pembina Institute
Box 7558
Drayton Valley, Alberta
Canada T7A 1S7
Phone: 780-542-6272

Within the Institute, Pembina Consulting is one of Canada's most-respected and innovative providers of solutions for policy-makers and corporate decision-makers seeking to enhance sustainability and competitiveness, and to support the shift to more sustainable production and consumption. Our consulting teams bring together core competencies in life cycle thinking, rigorous research, multi-stakeholder dialogue and innovative communications, in service of our mission of advancing more-sustainable energy solutions.

Acknowledgements

Undertaking a project of this size requires the support, direction and advice of a number of people. The authors would like to thank the following people:

Environment Canada's Advisory Committee

- Anne-Marie Chapman : Environment Canada, co-chair of the Advisory Committee
- Brian Titus : NRCan – Canadian Forest Services, co-chair of the Advisory Committee
- Emil Laurin : Environment Canada
- Robert Lyng : Ontario Power Generation
- Dan Puddister : Ontario Ministry of Natural Resources (Forest management)
- Kirsten Vice, National Council for Air and Stream Improvements (NCASI)
- Barbara Kishchuk : NRCan – Canadian Forest Services, Forest Soils
- Sebnem Madrali : NRCan – CanmetENERGY (Conversion)
- Pierre Sylvestre : Environment Canada – Oil, gas and alternate energy
- Karl Abraham : Environment Canada – Electricity and combustion
- Terry McIntyre : Environment Canada – Science and technology
- Devin O'Grady : Environment Canada – Oil, gas and alternate energy
- Alain Gingras : Environment Canada – Forestry, agriculture and aquaculture
- Heather MacLean : University of Toronto
- Shannon Berch : BC Ministry of the Environment

Other contributions

- Steve Colombo : Ontario Ministry of Natural Resources (Carbon modelling)
- Michael Ter-Michaelian : Ontario Ministry of Natural Resources (Carbon modelling)
- Denis Cormier : FPInnovations
- Jon McKechnie : University of Toronto
- Nathan Ayer : Dalhousie University

This analysis benefited from the participation and direction from the project's Advisory Committee, input and guidance from Environment Canada, and the expert advice of the people mentioned above. This report is better because of this wide variety of input; however, the authors acknowledge their responsibility for any errors or omissions.

Life cycle analysis of forest-based biomass at the Atikokan power plant

A full life cycle analysis and framework development of Ontario-sourced forest biomass for electricity and heat generation

Contents

List of Figures

List of Tables

Glossary of Terms

Term	Definition
Biomass	Biological material derived from living or recently-living organisms
Forest-based biomass	Biomass sourced from forests, predominantly trees. Forest-based biomass can include entire trees, or parts of trees — branches, bark, stems, needles and leaves
Biofibre	Terminology used in this report referring to forest-based biomass — both fibre from hardwoods and fibre from forest residue / slash
Forest residue / slash	Non-merchantable parts of a tree (i.e. tops of trees, branches, bark), or entire non-merchantable tree species, remaining after a forest harvest operation
Hog fuel	Unprocessed biofibre typically consisting of bark, branches and wood fibre
Coarse woody debris	Dead woody material in various stages of decomposition, located above soil, which is considered not to be self-supporting
White pellets	A higher-quality pellet made from the fibre from the interior trunk of a tree. White pellets typically have a lower ash content and a higher energy content than brown pellets
Brown pellets	A lower-quality pellet made from harvesting slash. Brown pellets typically have a higher ash content and a lower energy content than white pellets
Ontario Forest Management Unit (FMU)	Crown land that is divided into geographical planning areas for the purpose of forest management. Most FMUs are managed by separate forest companies under a Sustainable Forest License
Repowering	The conversion of a generating station to completely utilize a different fuel source than before the conversion
Co-firing	Using fuel sources in a generation station
Environmental release / emission	Releases of pollutants into air, water and soil, responsible for a variety of environmental impacts
Life Cycle Assessment (LCA)	A method developed to evaluate the mass balance of inputs and outputs of systems and to organize and convert those inputs and outputs into potential environmental impact categories. On the largest scale of a system, LCA models the complex interaction between a product and the environment from cradle to grave

Life Cycle Inventory (LCI)	The quantification of inputs and outputs of a system in terms of emissions reported on a volume or mass basis
Life Cycle Impact Analysis (LCIA)	A dedicated LCA methodology evaluating the significance of potential environmental impacts based on the LCI flow results
Ecoinvent	World's leading database with consistent and transparent, up-to-date Life Cycle Inventory data
ReCiPe	An LCIA methodological tool used to quantitatively analyze the life cycle of products/activities
Equivalence/Characterization factor	Science-based conversion factors used to convert and combine the LCI results into representative indicators of potential environmental impacts.

List of Abbreviations

Abbreviation	**Definition**
AAC	Annual allowable cut
CHP	Combined heat and power
CFS	Canadian Forestry Service
CTL	Cut-to-length harvesting
CWD	Coarse woody debris
DDC	Delimb, debark and chip
EC	Environment Canada
ECD	Electricity and Combustion Division
eNGO	Environmental non-government organization
FLB	Forest landbase
FMP	Forest management plan
FMU	Forest management unit
FRI	Forest Resource Inventory
GHG	Greenhouse gas
GLSL	Great Lakes–St. Lawrence
GS	Generating station
LCA	Life cycle analysis
LCI	Life cycle inventory
LCIA	Life cycle impact analysis

NPRI	National Pollutant Release Inventory
NRCan	National Resources Canada
OPG	Ontario Power Generation
OMNR	Ontario Ministry of Natural Resources
PCI	Planning Composite Inventory
PM	Particulate matter
SFL	Sustainable forest license

Executive summary

Motivation

Environment Canada (EC) received funding from the Clean Energy Fund Research and Development (R&D) program in the fall of 2010 to undertake an environmental life cycle assessment (LCA) to compare the use of forest-based biomass with coal for electricity production. This LCA biomass project was co-developed and chaired by EC's Electricity and Combustion Division (ECD) and the Canadian Forestry Services (CFS) of Natural Resources Canada, building on the complementary strengths of the two departments. As Canada and other provinces turn an interested eye to forest-based biomass as a replacement for fossil fuels in electricity/heat production, consideration of the tradeoffs and potential positive or negative environmental impacts is critical for advancing Canada's energy policies.

In a response to a public Request for Proposal, the Pembina Institute (Pembina) was hired as the biomass LCA expert in September 2011 to develop and produce a first iteration LCA analysis and product focusing on forest-based biomass for electricity/heat production.

Project Objective

The overall objective of the project was to apply LCA methods to ISO 14040/44 standards to better understand and quantify the potential environmental impacts of utilizing forest-based biomass for electricity/heat production compared to conventional fossil fuel sources (i.e. coal). The LCA would be used to evaluate potential positive or negative environmental impacts on air, water, land, soil, biodiversity / wildlife and other ecological goods and service from using biomass sourced from crown-land forests as compared to coal. Steps to achieve this objective included:

- Develop a *first-iteration* LCA product that is transparent, adaptable and can be further developed in the future. Focusing on a first-iteration product based on established LCA and ISO principles will provide a tool with the necessary transparency and standardization to facilitate modifications in the future.
- Produce an LCA product that is built to address a local and specific landbase that would produce biomass feedstock for an existing power plant.
- Include appropriate and relevant air, water, land/land-use change, soil, biodiversity/wildlife environmental impacts that would cover trade-offs between the use of forest-based biomass and coal across a spectrum of environmental values.
- Push the boundaries of conventional LCA methods typically used to assess environmental impacts of biomass use to include more complex and non-traditional impacts related to soil productivity, biodiversity and wildlife.

However, it must be borne in mind that while a scientific LCA produces one tool for facilitating decision-making processes, it should not be considered the only option, especially considering the difficulties encountered when incorporating more challenging and complex environmental impacts that are not yet commonly included in LCA because of lack of methods and/or data.

Project Background

With the Government of Ontario committing to eliminating coal-fired electricity production by the end of 2014 and Ontario Power Generation (OPG) committing to convert the Atikokan Generating Station in Northwest Ontario to burning wood pellets, this power plant was selected as a real-life case study for this LCA project. Four forest management units (FMUs) within close proximity to the Atikokan Generating Station that would potentially provide the required biofibre were selected as the fuelshed.

Six bioenergy scenarios were developed to cover a plausible range of different biofibre resources, harvesting and energy conversion conditions. Two specific biofibre resources were targeted – road-side forestry slash (which, within this LCA, is considered to be a byproduct of the traditional forestry industry) and unmerchantable hardwood species (which have no market value within the current forestry context). Two different harvesting rates were also defined based on the region's maximum annual allowable cut (AAC): one approximately 75% of the AAC and one close to the maximum AAC (95%). Four energy conversion scenarios were also targeted: 100% combustion of white pellets for electricity generation; 100% combustion of brown pellets for electricity generation; co-firing (65% combustion of white pellets and 35% combustion of coal) for electricity generation; and combined heat and power (using hog fuel) for electricity/heat generation. Lignite coal from open-pit mines in Saskatchewan (the current source of coal for the Atikokan Generating Station) was selected as the fossil fuel reference case.

An important and fundamental principle of this LCA is that the coal reference case and the bioenergy scenarios are set within the context of industries that are fully compliant with federal and provincial regulations. The LCA is therefore best considered as a strategic-level modelling analysis that quantifies potential environmental impacts and should not be considered or interpreted as an operational-level analysis or critique of specific forest management practices in Ontario or coal mining practices in western Canada. Rather, this work should be considered an evaluation of alternative management and resource strategies that are within current regulatory frameworks.

	Biofibre harvest scenario	**Conversion scenario**
Bioenergy scenario A	BH2 – approximately 70% utilization of the AAC. Biofibre extracted from forest as chips.	100% white pellets for electricity generation
Bioenergy scenario B	BH3 – approximately 95% utilization of the AAC. Biofibre extracted from forests as logs.	100% white pellets for electricity generation
Bioenergy scenario C	BH2	Co-fire - 65% white pellets / 35% coal
Bioenergy scenario D	BH3	Co-fire - 65% white pellets / 35% coal
Bioenergy scenario E	BH1 – roadside slash. No increase in % utilization of the AAC. Biofibre extracted from forest as chips	100% brown pellets for electricity generation

Bioenergy scenario F	BH1	100% hog fuel for combined heat and power

Potential environmental impacts

Through an initial research phase on biomass utilization for electricity/heat production – with a focus on the most relevant traditional and non-traditional environmental impacts measured in LCAs as well as LCA methodologies and tools available –the following table summarizes the initial environmental impacts selected in this first iteration:

Environmental impact	Primary impact category
Climate change	Air
Terrestrial acidification	Land/soils
Freshwater eutrophication	Water
Terrestrial ecotoxicity	Land/soils
Freshwater ecotoxicity	Water
Fossil fuel depletion	Resources
Natural land transformation	Land-use / Land-use change
Seral stage distribution	Biodiversity (a measure of forest structure)
Coarse woody debris	Biodiversity (a measure of forest structure)
Forest fragmentation	Biodiversity (a measure of intactness)

Modelling platform

Three distinct modelling components were developed in this project to quantify these potential environmental impacts:

- **ReCiPe methodology and Ecoinvent** –The ReCiPe methodology and Ecoinvent database were used as the principle framework for quantifying the climate change, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, fossil fuel depletion and natural land transformation environmental impacts.
- **FORCARB-ON –**FORCARB-ON was used to estimate the impacts to forest carbon stocks resulting from continuous biofibre extraction, and these forest carbon results were incorporated into the climate change environmental impact to accurately account for the greenhouse gas (GHG) impacts from biofibre harvesting.
- **ALCES® –**The ALCES® platform was used for quantifying the seral stage, forest fragmentation and coarse woody debris environmental impacts.

The LCA modelling in this work was performed over 100 years to primarily account for forest dynamics, extrapolated from 5- and 10-year forest management plans (FMPs) specific to the four FMUs in Northwest Ontario. With this extrapolation comes the acknowledgement that this work does not model what *will* happen, but rather what *may* happen based on base information and data available from the FMPs and the further assumptions defined in this work.

Results and Discussion

Forest carbon and GHG results

Forest carbon results show that the four FMU landbase is predominately a source of carbon throughout the planning horizon when continuous harvest rates are applied for the two different biofibre sources. For roadside slash, there is a small continuous decrease in forest carbon and this decline is most significant early in the planning horizon and levels off. For standing trees in the BH2 scenario, the landbase is a source of carbon for the first 75 years then transitions to a carbon sink for the remainder of the planning horizon. For BH3, there is a further decline in forest carbon and the landbase is a source of carbon for the first 65 years then transitions to a carbon sink for the remainder. The table below summarizes the short-, mid- and long-term impacts to forest carbon.

Bioharvest scenario	Short-term (10 years) – Mt carbon	Mid-term (50 years) – Mt carbon	Long-term (100 years) – Mt carbon
BH1 (slash)	-1.3	-4.3	-6.3
BH2 (standing trees, 75% AAC)	-4.6	-16.0	-15.9
BH2 (standing trees, 95% AAC)	-9.1	-30.2	-28.5

The life cycle GHG emission intensities (kg CO_2e / MWh electricity produced) for the upstream activities (commissioning, biofibre harvest, comminution, silviculture, transportation, pelletization and combustion) associated with the bioenergy pathways varying depending on the biofibre resource utilized and the conversion scenario. Relative to the life cycle of coal (1,253 kg CO_2e / MWh), GHG emission intensities are approximately 95% lower for slash (65 kg CO_2e / MWh), 91% below for standing trees (109 kg CO_2e / MWh) and 60% lower for co-firing (499 kg CO_2e). These life cycle results are in-line with other life cycle studies on forest-based biomass for energy. The above GHG emissions exclude biogenic carbon emissions and change in the forest landbase based on the assumption that carbon emissions from biomass are instantaneously re-sequestered by the landbase.

However, when biogenic carbon emissions and the changes to forest carbon are taken into consideration, the GHG emission intensities increase considerably and only roadside slash offers a GHG emission reduction benefit over coal. Relative to the life cycle of coal (1,253 kg CO_2e / MWh), GHG emission intensities are approximately 66% lower (420 kg CO_2e / MWh) for slash, 5% lower for standing trees (1,187 kg CO_2e / MWh) and also 5% lower for co-firing (1,187 kg CO_2e / MWh).

When comparing the cumulative GHG emissions of the bioenergy scenarios to coal, there is also a significant GHG emission difference between roadside slash and standing trees. For standing trees, the cumulative GHG emissions from biomass are increasing and higher than coal for the first 45 years (2060) at which point they begin to decline. At the end of the planning horizon, GHG emissions from biomass are 0.6 Mt higher relative to coal. For roadside slash, there is an immediate GHG emission reduction benefit compared to coal. At the same 45 year mark (2060), roadside slash offers a reduction of -55.8 Mt CO2e over coal.

Acidification, eutrophication and ecotoxicity environmental impacts

For all bioenergy scenarios, there is a decrease in potential terrestrial acidification compared to coal primarily because of the reduced NOx and SOx emissions in biofibre combustion compared to coal combustion.

There is also a decrease in potential freshwater eutrophication for all bioenergy scenarios compared to coal primarily because of the high phosphorous releases from coal mine tailings. The environmental releases of phosphates from mine tailings is modelled using Ecoinvent data as tailing information specific to open-pit mining in Western Canada was limited.

There is a surprising increase in the potential for terrestrial ecotoxicity increases when fuel switching to biofibre combustion. All six biofibre scenarios result in higher terrestrial ecotoxicity releases compared to coal. This is a highly counter-intuitive result considering the common perception of coal being a highly "dirty" fuel. These high terrestrial ecotoxic releases from biofibre is driven by Ecoinvent release factors of zinc, phosphorus and copper. Ecoinvent is using European-based data that are geographically dependent (i.e. the content of elements within the biofibre will vary by jurisdiction). It is very likely that biofibre combustion in Canada will exhibit a different emissions profile of substances compared to biofibre combusted in Europe. A sensitivity analysis was performed that replaced Ecoinvent emission factors with NREL and similar results were obtained.

The potential to freshwater ecotoxicity impacts decreases for all of the six bioenergy scenarios compared to coal. This result is mainly driven by the high ecotoxic releases from the disposal of coal ash. Coal ash disposal is modelled using an Ecoinvent residual material landfill that contains a base seal and leachate collection system. The freshwater ecotoxicity releases in a Canadian or Ontario landfill will vary from what is modelled and will depend on various site-specific issues.

Fossil fuel depletion and Natural land transformation

All bioenergy scenarios also see potential reductions in fossil fuel depletion and natural land transformation compared to coal. For fossil fuel depletion, reductions are primarily a result of the replacement of coal (considered a fossil fuel in Ecoinvent) with biofibre (not considered a fossil fuel in Ecoinvent) and are approximately 93% for bioenergy scenarios A, B, E and F. There is an increase in fossil fuel utilization in the bioharvest procurement phases because of the fuel required to harvest, chip, extract and process the biofibre compared to coal.

For natural land transformation, there is a general decrease for all bioenergy scenarios compared to coal. Investigation and full inclusion of all land occupation and land transformation activities as per the ReCiPe definition and methodology requires further work; hence results for natural land transformation should be considered preliminary.

Forest Structure

In this work, forest structure was measured in two ways; age class (seral) distribution and coarse woody debris

Current harvesting rates and practices will reduce the amount of old and mature biofibre on the merchantable landscape over time as the forest becomes more regulated. This proceeds at a pace that could be considered comparable to the natural disturbance regimes which forest management attempts to emulate. However, the BH2 scenario brings an 80% reduction in stands aged 121 – 140 on the merchantable forest landbase within 50 years as compared with current practice. The BH3 scenario reaches this same state in just over 30 years. Similar but less dramatic outcomes are forecast for mid-seral age classes while early seral stands aged 20 years or younger increase in prevalence when comparing BH2 and BH3 to current practice. BH2 forecasts a 41% increase in early seral forest relative to current practice while BH3 forecasts a 61% increase. The rate of change is greatest in the second half of the forecast but this sustained predominance of early seral stands may have a more far reaching effect.

Accumulation CWD declines in BH2 by 78% and in BH3 by 89% in 50 years compared with current practice. Perhaps more alarming for long term biodiversity is that this change is persistent through the planning horizon with BH2 reduced by 92% in 100 years and BH3 by 96% - essentially a full order of magnitude within the lifespan of a generation of forest stands. If the simulated management strategies were to continue beyond 100 years it is unlikely that this trend would reverse and therefore this change could be considered permanent. Clearly, those elements of biodiversity dependent on older forest with complex structure and high amounts of accumulation CWD will have significantly fewer opportunities. There may also be significant implications for nutrient cycling in the long term particularly for the BH3 scenario as the regenerating watersheds see a significant and sustained change in ground level CWD.

Fragmentation

Fragmentation is forecast to increase in both bioharvest scenarios. Linear networks of roads, edge associated with harvest areas and burns all contribute to forest fragmentation. The analysis shows that relative to current practice, the BH2 and BH3 scenarios result in significant and steady increases landscape fragmentation. The primary drivers of this increase are tertiary roads and cutblock edge. Tertiary road impacts may or may not persist within harvested areas over time although they were assumed to have no edge contributions after 20 years in this study – which is considered a conservative estimate. In BH3, fragmentation is 69% higher than current practice within 50 years and continues to increase to 134% by year 100. The rate of increase is not expected to be sustained indefinitely but the increased amount of fragmentation is. With a long term sustained harvest level, the amount of tertiary roads needing to be built will parallel the continuous creation of new harvest areas. So as with structure, the landscape change is expected to be persistent which deviates substantially from what would be expected within the bounds of range of natural variation.

The results of this study, especially the biodiversity components, must be considered within the context that all activities assessed are within the approved legislative and regulatory frameworks for resource development within the respective jurisdictions. It is noted that none of the biofibre harvest scenarios exceed the maximum AAC that has been determined through detailed forest management planning to be sustainable in the long term and to adequately account for non-timber values. This analysis is considered somewhat conservative because the starting inventory of road networks is likely significantly underestimated and because of this, the total landscape fragmentation may be significantly higher over time than has been forecasted.

When considering the magnitude of change between the coal and biomass cases, the area affected is an important consideration. The surface mining in Saskatchewan will have a 310 hectare footprint whereas the biomass forest harvesting will alter roughly 113,000 times this.

It is also acknowledged that ecosystems vary widely across Canada. Practices and requirements will vary accordingly and are likely to be changed through time as a result of adaptive management. While this approach can be ported to other areas in the country, the metrics and targets must be flexible and reflect these differences.

Key Findings

The following points highlight some of the key findings from this work:

- Incorporating potential biodiversity and other non-traditional environmental impacts into an LCA is extremely challenging and complex. This work makes an initial attempt, and further integration of biodiversity impacts into a life cycle approach is warranted to maximize the value of this information.
- If assuming carbon neutrality (i.e. the biogenic CO_2 emissions for biomass are excluding from the accounting and assumed to be instantaneously absorbed by the forest), bioenergy offers a significant net reduction of GHG emission compared to coal.
- When not assuming carbon neutrality and including forest carbon in the GHG accounting, bioenergy offers a lower reduction of GHG emissions compared to coal and depending on the biofibre sourced used, could actually have higher GHG emissions. The GHG emissions from bioenergy are also very time dependent because of forest carbon component and the dynamic nature of a landbase under study.
- Depending on the source of biofibre, the GHG impacts are quite different. Utilizing roadside slash has a definite GHG reduction benefit over coal. When harvesting trees, bioenergy has higher GHG emissions relative to coal in the early phases of the planning horizon. In this study, GHG emissions from bioenergy are greater than coal for up to 45 years.
- Generally, for all bioenergy scenarios, there is a decrease in terrestrial acidification, freshwater eutrophication, freshwater ecotoxicity, natural land transformation and fossil fuel depletion, relative to coal. These current results are quite dependent on the localized data that has been integrated into the Ecoinvent modelling with some of the biggest contributors being fuel (both coal and biofibre) combustion, environmental releases in coal tailings and management coal ash.
- For all bioenergy scenarios, there is an increase in terrestrial ecotoxicity emissions relative to coal. This result is driven by the useage of Ecoinvent emission factors for biofibre combustion as there is currently no local data specific to chemical composition or environmental emissions from pellet combustion.
- The overall interpretation that BH3 offers more risk to biodiversity is not an absolute statement as there has been no assessment to determine if these quantified environmental impacts exceed acceptable thresholds.
- Elements of biodiversity with a preference or perhaps obligation for early seral stands will have increased opportunities in the long term and this is not likely to change beyond 100 years. However, given the relatively long natural disturbance cycles for these ecosystems, this increased predominance of early seral stands may well be outside the bounds of natural range of variance.
- The biodiversity changes contemplated in the biofibre harvesting forecasts are not insignificant with some metrics exceeding 100% change over the forecast period and

several measured more than three-quarters different within 50 years. Sharp changes in ecosystem composition, structure and/or fragmentation within the short term bear more risk than long-term change because there may be little or no time to adapt or reverse negative conditions.

- It is clear that there are significant differences in biodiversity performance across the scenarios – with the exception of old forest – which is largely insensitive to BH2 and BH3. If changes to these key biodiversity metrics can be assumed to bring with them increased risk relative to current practice, then BH2 carries a greater magnitude of risk than current practices and BH3 evokes more risk than BH2.

Data Uncertainty

- Data quality for the three landscape-level indicators (seral stage, fragmentation, CWD), climate change (and forest carbon) and terrestrial acidification midpoints are quite good. The remaining five environmental impacts – freshwater eutrophication, terrestrial / freshwater eutrophication, fossil fuel depletion and natural land transformation all have relatively poor data quality scores due to their high dependence on Ecoinvent emission factors.

Recommendations on Next Steps

The following points highlight the top key recommendations for future work:

- **Coal reference case and natural gas reference case** – With the results and interpretation of results being dependent on high quality fossil fuel reference cases, further work is recommended to increase the data certainty for the coal reference case, specifically on environmental releases of phosphorous for coal tailings. It is also recommended to include a natural gas reference case to further aid the decision making process of bioenergy being a replacement fuel for fossil fuels.

- **Forest carbon accounting frameworks –** With forest carbon being a significant contribution to overall GHG emissions, research into the most appropriate forest-based carbon accounting methodologies is recommended.

- **Further integration of traditional and non-traditional environmental impacts** – This first iteration makes an initial attempt at combining traditional and non-traditional environmental impacts into life cycle thinking. There are unique challenges with this goal and developing a methodology to leverage these already quantified indicators and potential new indicators will be extremely useful.

- **Particulate matter and human health** – It is recommended to advance the midpoint and endpoints quantified through the ReCiPe framework to include particulate matter and human health, especially considering the open combustion of slash piles and their effect on local air quality.

- **Inclusion of additional environmental impacts** – With a first iteration framework developed, there are several additional environmental impacts that could be incorporated into this work. The top recommended additional impacts worth consideration include community-level environmental impacts (leveraging the landscape-level impacts), particulate matter (and human health endpoint), water hydrology (integrating water quality and quantity to track water and nutrient flows) and soil productivity / nutrient cycling.

- **Investigation into key Ecoinvent processes and high uncertain data –** Freshwater eutrophication, terrestrial / freshwater ecotoxicity, fossil fuel depletion and natural land transformation have been identified as the top five environmental impacts with the lowest data quality. If it is of the option of EC that these impacts are important for proper decision making on bioenergy, gathering localized data and emission factors for these impacts should be completed.

1. Introduction and project overview

In the fall of 2010, Environment Canada (EC) received funding from the Clean Energy Fund R&D program[1] (NRCan) to undertake an environmental Life Cycle Assessment (LCA) to evaluate the potential environmental impacts from utilizing forest-based biomass for electricity/heat production compared to fossil fuels.

This project was supported by an Advisory Committee that aided in the development of the project scope and guided the major decisions of the project. Research and data gathering subprojects collaboratively identified by the Advisory Committee were carried out at the start of the project process and are referred to throughout this report.

The Pembina Institute (Pembina) was hired as the biomass LCA expert in September 2011 to design, implement and deliver this first iteration LCA analysis of forest-based biomass for electricity/heat production.

1.1 Project background and purpose

The Government of Canada has committed to reducing annual greenhouse gas (GHG) emissions by 17% below 2005 levels by 2020. This commitment is needed to help mitigate the effects of climate change the world is seeing primarily because of our continued exploration for and use of fossil fuels.

Although Canada has substantial hydro-electric power generation, several provinces including Nova Scotia, Ontario, Saskatchewan and Alberta still rely on coal to generate electricity. Ontario has only moderate exploitable wind and solar resources and limited scope for further hydropower development, but does possess, like other provincial jurisdictions, a world class forest resource. Forest-based biomass for power generation may offer a key path forward for GHG reduction in Ontario — if sourced, used appropriately and properly accounted for in carbon accounting frameworks. With the Government of Ontario committing to eliminate coal-fired power by the end of 2014, Ontario Power Generation (OPG) is looking at using biomass as a fuel-switching alternative for their four coal-power generation stations. The Atikokan generation station (GS), one of four OPG coal-fired power plants, is the first to be considered for this conversion.

Utilizing forest-based biomass could have positive or negative impacts[2] on forest productivity and regeneration capabilities, hydrology, air, wildlife and biodiversity and land use, when compared to fossil fuels like coal or natural gas. If there are some net benefits associated with

---

[1] http://www.nrcan.gc.ca/energy/science/programs-funding/1482

[2] It is important to note that the term impacts usually implies negative impacts, but in the context of this work, environmental impacts could be positive or negative

using forest-based biomass — and the potential environmental impacts and related ecosystem quality and health implications can be minimized — then a biomass energy strategy could be a possible lever for climate emissions reduction relative to fossil fuels.

A fundamental question that must be answered when considering fuel switching from the fossil fuels that are currently used can be summarized as:

> *"What are the potential environmental air, land, water and ecosystem impacts of sourcing biomass from forests to produce electricity and what are the tradeoffs when comparing this option to the environmental impacts from coal or natural gas*?"

Central to this question is the theme of "sustainable biomass". To carve a path forward, decision-makers need the ability to assess and find pathways to mitigate the trade-offs and maximize the benefits anticipated from increasing the use of Canada's forests and the goods and services they provide. Utilizing forest-based biomass is a divisive issue in regards to both climate change and forest conservation analyses with many diverse opinions and positions amongst environmental and conservation organizations, energy companies promoting green renewable technologies, and utilities looking at using biomass for energy generation.

Science-based insight into the above question can be aided by the application of an environmental life cycle assessment (LCA) methodology: a full cradle-to-grave analysis of potential environmental impacts (i.e. air, hydrology, soil, land/land use change, wildlife habitat and biodiversity) of using biomass for heat and/or electricity production. An environmental impact analysis provides qualitative and quantitative information about the relative importance and scale of the effects on the potential environmental parameters quantified. Specific to this work, this scientific approach gives insight into the full upstream, usage and downstream processes necessary to source, transport, utilize, dispose of, and regrow a forest-based biomass fuel, and provides a platform for comparison against other conventional fossil fuel choices.

To compare the potential environmental impacts of using biomass to fossil fuels such as coal, LCA methodologies and analyses have been conducted for GHG and other air emissions. However, environmental sustainability encompasses a wide range of environmental considerations beyond traditional air emissions and is much more difficult to quantify. A great deal of research on the sustainability of biomass has been carried out, but this work has often been in isolation based on the specific concerns of different sectors; this works against the holistic approach that is needed to define biomass sustainability. This projects attempts to include other relevant potential environmental impacts within an LCA framework that are more challenging to incorporate and quantify.

1.2 Project objectives

This LCA initiative was undertaken to better understand and quantify, through a scientific process, the potential environmental impacts to air, land, water, soil and wildlife associated with using forest-based biomass, and to compare these potential environmental impacts to other fossil fuel sources.

The primary objective of this LCA is to:

1. **Develop a first iteration environmental LCA.** This first and foremost goal of this work is to produce a first iteration of an environmentally-focused LCA on the combustion of

biomass for electricity production in Canada, with specific focus on the Atikokan GS as a case study. The LCA will be structured as a cradle-to-grave analysis, including but not limited to GHG emissions and sinks, other air pollutants emissions, environmental impacts on surface and groundwater quality, water use, and environmental impacts on biodiversity and soils. The term *first iteration* highlights the vision that this LCA analysis is to continue with future iterations. A strong focal component of this initial project is to design, develop and apply an LCA framework and methodology that can be carried forward.

A secondary smaller objective of this work is to produce a first iteration list of criteria (metrics) that could be considered when evaluating environmental impacts of biomass production. Section XXX includes an initial and brief discussion of criteria that could be considered when evaluation environmental impacts.

1.3 Outline of report

This report is structured into seven sections:

- Chapter 1 provides an introduction and overview of the project.
- Chapter 2 summarizes the project scope and the background details of this project.
- Chapter 3 discusses the LCA methodology, approach and potential environmental impacts quantified in this work.
- Chapter 4 presents the potential environmental impact results relative to coal and provides an interpretation of the results.
- Chapter 5 presents a comparison of the potential environmental impacts between the bioenergy scenarios and provides an interpretation of the results
- Chapter 6 provides a sensitivity analysis of identified key areas, and an uncertainty assessment.
- Finally, Chapter 7 provides a summary of key findings, discussion and recommendations on next steps.

2. Project scope and details

2.1 Project scope

There are several scope dimensions to this work, summarized below.

First iteration of a Biomass LCA

This work focuses on adopting and applying an LCA methodology to develop a first iteration biomass LCA model that will meet the overall project objectives and also provide a modelling platform to facilitate future work in this area. This project focuses on the selection and quantification of key potential environmental indicators and also identifies data gaps, limitations and an uncertainty analysis so further work can be identified.

Bioenergy and coal reference case processes

This work uses OPG's Atikokan thermal electricity generation station (GS) as a case study. Thermal electricity GSs utilize the energy in the fuel source to produce electricity. Water is heated, turns into steam and spins a steam turbine which drives an electrical generator. In the bioenergy scenarios in this work wood pellets are the fuel source, while lignite coal is the fuel source in the coal scenario. Utilizing coal to produce electricity is considered as the *reference case* in this analysis. Included in this reference case is the business-as-usual (BAU) forestry industry practice that harvests a certain amount of biofibre for traditional forest products, defined by the first biofibre harvest scenario (BH0)[3]. This BAU practice includes the roadside burning of forestry slash.

Bioenergy scenarios

To facilitate a comparison against different feasible sources and utilization of biofibre, three specific biofibre harvesting scenarios, in addition to the BAU scenario, and four energy conversion scenarios were defined. The biofibre harvesting scenarios are further defined in Section 2.2.2 and the energy conversion scenarios are defined in Section 0. These three biofibre scenarios and four conversion scenarios allow for a possible 12 bioenergy scenarios. This work focuses on six selected bioenergy scenarios, presented in Section 2.2.5.

Five of the six bioenergy scenarios represent the processing of biofibre, using thermal combustion, in the GS to produce electricity. The sixth bioenergy scenario represents the processing of biofibre, also using thermal combustion, in a hypothetical combined heat and power (CHP) facility to produce both electricity and heat.

[3] The BH0 scenario is defined further in Section 2.2.2.

Fossil fuel reference case

As mentioned above, this work includes a hypothetical fossil fuel reference case in order to provide a comparison of the bioenergy scenarios against a 'business-as-usual' reference case. The fossil fuel reference case defined for this work is coal, sourced from open-pit mining in Western Canada[4]. More information on this is presented in Section 2.4

Potential environmental impacts analysis considering a LCA approach

The focus of this work is to apply LCA thinking and methodology to estimate the potential incremental environmental impacts of utilizing biofibre sourced from Ontario crown land forests — specifically air, hydrology, land/land use change and soils, as well as more complex issues surrounding wildlife habitat and impacts on biodiversity.

Information gathered from a report by the Pembina Institute[5] (a subproject to this overall LCA project) conducted and presented online research and a survey of environmental and conservation organizations focusing on climate, energy issues and forest conservation. The following three themes emerged as the most significant environmental issues for these groups around forest-based biomass:

- Biodiversity, wildlife habitat and endangered species
- Soil fertility and forest productivity
- Carbon accounting frameworks and GHG emissions

There are many examples and applications of applying an LCA framework to potential environmental impact categories such as air emissions, impacts to water quality / quantity and environmental impacts to soils. However, the application of a scientific LCA methodology to quantify the potential environmental impacts to more complex forest ecosystem dynamics such as forest soil and nutrient cycling, wildlife and biodiversity is an area of LCA science that is still evolving and that has limited establishment and adopted methodologies. Regardless of this, it is critical to incorporate a methodology to enable an initial quantitative analysis of these more complicated forest ecosystem issues.

Through further research in this project on the state of the science, data availability, subproject report information[6,7,8] and project timelines, we determined that an assessment of potential environmental impacts related to landscape-level biodiversity was a key area that could be incorporated in this first iteration. Analysis of the effects biofibre utilization could have on key landscape metrics is tackled using new and innovative approaches, considering the scientific

---

[4] This reference case is considered hypothetical since electricity generation from coal is being phased out in Ontario by 2014.

[5] Internal EC report, *eNGO and Conservation Group Outreach on Biomass*, Unpublished. The Pembina Institute, 2011

[6] Internal EC report, *The effect of forest harvest residue removal on biodiversity in northwest Ontario with special reference to the hardwood component*, Unpublished. McCavour, McNair, Tittler, Gervais, Solarik, Greene, Messier

[7] Internal EC report, *Hydrological Implications of forest biomass use*. Unpublished, JM Buttle, 2011

[8] Internal EC report, *Assessment of the potential impacts of using woody biomass for heat and/or electricity production in the context of a biomass LCA in the Atikokan power generating station supply lake chemistry*¸ Unpublished, S. Watmough, T. Philips

application of how to deal with these more complicated impacts from an LCA perspective is still evolving. While these aspects are quantified, limitations in data precluded them being computed at the same level of precision and accuracy as with the other results of the LCA, which were undertaken using traditional LCA approaches. This is discussed in more detail in Section 3.2.2.

This overall LCA analysis therefore applies an LCA framework and methodological approach to the conventional and non-conventional potential environmental impacts where research, best practices and examples guide and support the applied LCA methodologies.

This modelling analysis is not possible without numerous assumptions necessary in order to state not what will occur, but what may occur throughout the modelling timeframe. There were several initial project decisions, initial subprojects and concurrent subproject that fed into this overall LCA project that required their own assumptions. Appendix F summarizes the most salient and important assumptions in this work.

2.1.1 Areas outside of project scope

There are several areas worth noting that are considered to be out of scope for this first iteration LCA.

- This LCA is not an operational modelling assessment but rather a strategic modelling assessment to quantify the potential environmental impacts associated with biomass and coal.
- Critiquing existing forest management policy, practices and FMPs and commenting on their applicability to sustainability standards and criteria.
- Other sources of biofibre including salvage trees, agricultural biomass or biofibre sourced from private woodlots.
- Environmental comparison of bioenergy scenarios to other renewable energy technologies including wind, solar and geothermal.
- Soil productivity / nutrient cycling and the impacts on forest dynamics as a result of biofibre harvesting. It was determined early on in the project that there are significant data gaps to support analysis of long-term soil productivity and nutrient cycling forecasting.
- Impacts on the boreal forest and its carbon cycle as a result of climate change.

2.2 Bioenergy scenarios

With different volumes and sources of biofibre available as well as options for converting the energy in the biofibre to usable electricity and heat, it is important to understand the environmental tradeoffs of these various options. During the initial stages of this project, several biofibre harvesting and conversion scenarios were identified[9] that represented realistic scenarios and options for the Atikokan GS. The details of the biofibre supply modelling, biofibre harvest and conversion scenarios are discussed below.

[9] Internal EC report, *Bioenergy Scenario Development for Atikokan Supply Region,* Unpublished. Heather MacLean 2011

2.2.1 Biofibre supply and modelling

Four existing forest management units (FMUs) from crown land in Northwest Ontario were selected as the supply area for the biofibre. This biofibre would be processed into wood pellets or hog fuel and used in the Atikokan GS[10] to produce electricity. These four FMUs were selected as the landbase for this analysis because of their close proximity to the Atikokan GS. These FMUs are Crossroute, Dog River–Matawin, Sapawe and Wabigoon FMUs and the location of the Atikokan GS are shown in Figure 1.

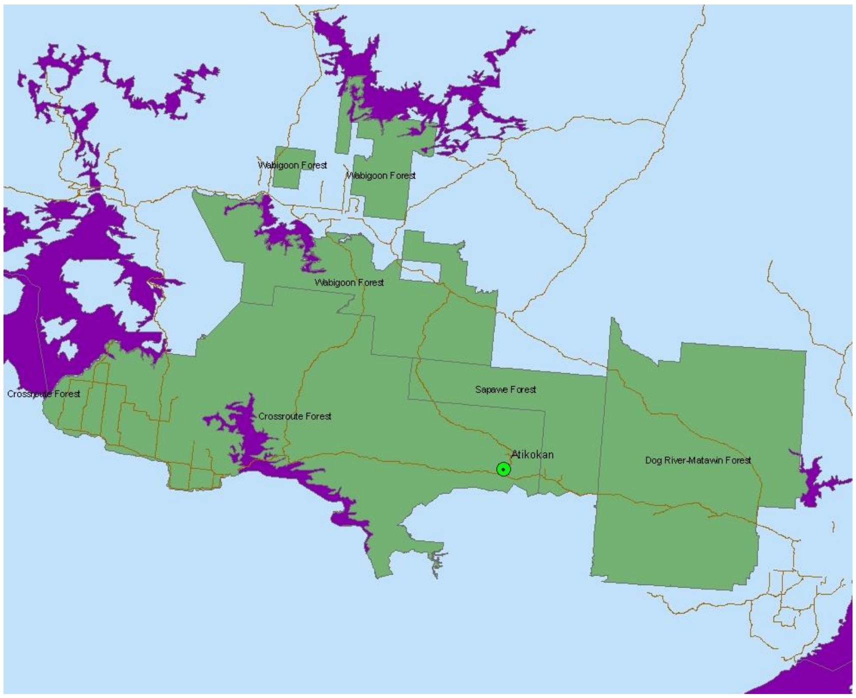


Figure 1. FMUs considered for the biofibre supply analysis

Source: FPInnovations 2011

Based on annual biofibre volumes, it was assumed that two pellet plants would be required to produce the annual supply of wood pellets. Fort Francis and Atikokan were selected as the location of these two theoretical pellets plants. Under the scenarios, the biofibre sourced from the FMUs is sent to the closest pellet plant, either Fort Frances or Atikokan, depending which FMU the biofibre is sourced from. Once the pellets are produced, they are delivered to the Atikokan GS. In one bioenergy scenario hog fuel is sent directly to the hypothetical Atikokan CHP facility since no further processing of the biofibre is required. Figure 2 provides a visual representation of the division line for what facility the biofibre would be sent to.

[10] Five of the six scenarios defined in this project look at generating electricity at the Atikokan GS, using biofibre converted to wood pellets. The sixth scenario looks at generating both heat and electricity through a theoretical CHP that uses hog fuel.

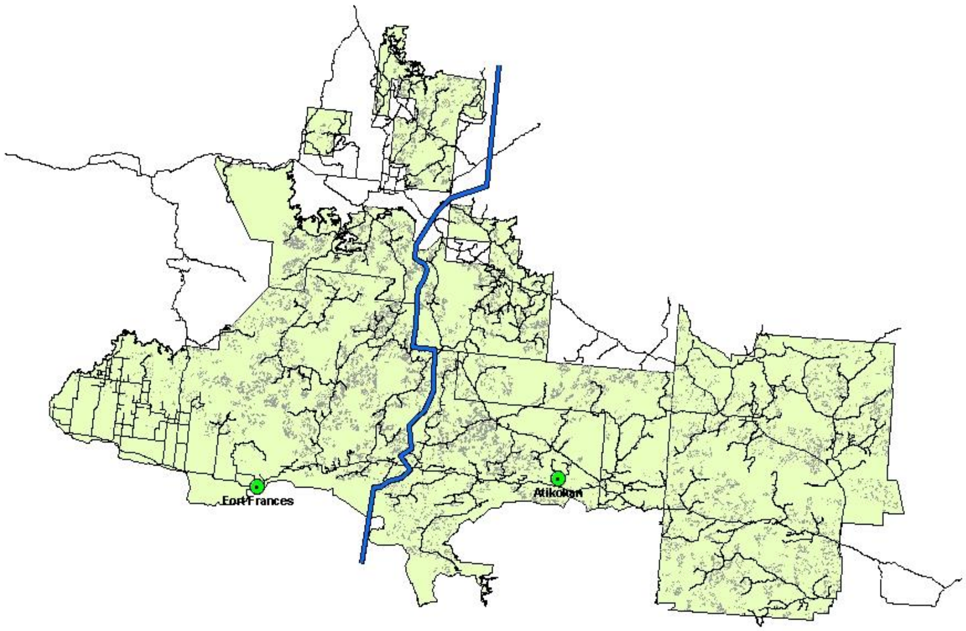


Figure 2. Supply boundary (blue line) for the two hypothetical pellet plant installations located in Fort Frances and Atikokan

Source: FPInnovations 2011

FPInnovations,[11] which focuses on developing new markets opportunities within a framework of environmental sustainability, modelled two important components in this work: the biofibre volume estimates based on utilization rates and the GHG emissions related to the forestry, comminution and transportation (transporting the biofibre from the FMUs to the pellet plants)[12]. The Biomass Opportunity Supply (BiOS) model was used to forecast the volume of recoverable biofibre, both roadside slash and white biofibre from hardwood species from each FMU, based on defined utilization rates and percentage increases in the FMU's Annual Allowable Cut (AAC).[13] Data needed to perform this work included growth and yield curves and forest management planning plans (FMPs) for the four FMUs. It is assumed that this volume of biofibre is available and constant year to year over the 100-year planning horizon. The forecasted biofibre volumes are based on the five- and ten-year FMU FMPs. Although this LCA analysis has a temporal analysis timeline of 100 years, there is no spatial data available that predicts the future harvesting location cut blocks. Therefore, the 10-year information from the FMPs was replicated for the remaining 90 years of the planning horizon to estimate the forest carbon resulting from the annual biofibre harvesting. For more detailed information on the biofibre modelling and biofibre availability estimates, refer to the FPInnovations report.

The BiOS modelling and the forest carbon modelling (discussed further in Section 2.3) use a hypothetical future start date of 2015. The data used to model the forest stands from the current time to a forecast 2015 is based on most recent FMU forest management plans (FMPs). For this modelling work, it is assumed that future stands scheduled for harvest would have attributes

---

[11] http://www.fpinnovations.ca/

[12] Internal EC report, *Summary_Forestry and Biomass_Final Jan 30*, Unpublished. FPInnovations 2012

[13] Refer to Section 2.2.2.1 for more detail

similar to the stands identified in the current FMPs. The forest stands were "rolled forward" by increasing the age of each stand from their age of the last forest management planned to the year 2015.

The roadside slash generated and available for the BH2 and BH3 harvest levels are a result of full-tree harvesting and DDC operations. All forestry slash generated from CTL is left in the forest and is not considered available. For the BH2 and BH3, for full-tree harvesting, it was assumed that 30% of unmerchantable biofibre was left in the cutblock. For DDC harvesting, it was assumed that 25% of unmerchantable biofibre was left in the cutblock[14].

Table 1 and Figure 3 summarize the total biofibre for each FMUs. For the road slash biofibre, it is estimated that an average (85% average for the four FMUs) of the roadside slash is considered technically and economically available. The amount of roadside slash (BH1, BH2 and BH3)[15] listed in these tables reflects this available percentage. It is important to note that two of the harvest scenarios (BH2 and BH3), recoverable biofibre (both slash and wood) is based on the *incremental* harvest rates above BH0 for these scenarios.

Table 1. Amount of recoverable (available) biofibre for each biofibre harvesting scenario by FMU (relative to BH0 baseline)

FMU	Recoverable biofibre (oven-dried tonnes (ODT) / year)				
	BH1	BH2		BH3	
	Slash	Slash	Wood	Slash	Wood
Sapawe	19,418	9,425	19,456	13,811	37,827
Wabigoon	89,137	20,333	42,377	24,326	78,824
Dog River–Matawin	138,445	45,147	80,068	49,349	130,399
Crossroute	196,936	71,165	154,995	105,518	340,385
Total	**443,936**	**146,070**	**296,896**	**193,005**	**587,436**

[14] Modelling assumptions made by FPInnovations and used in the BIOS model

[15] Refer to Section 2.2.2 for details on the biofibre harvest scenarios

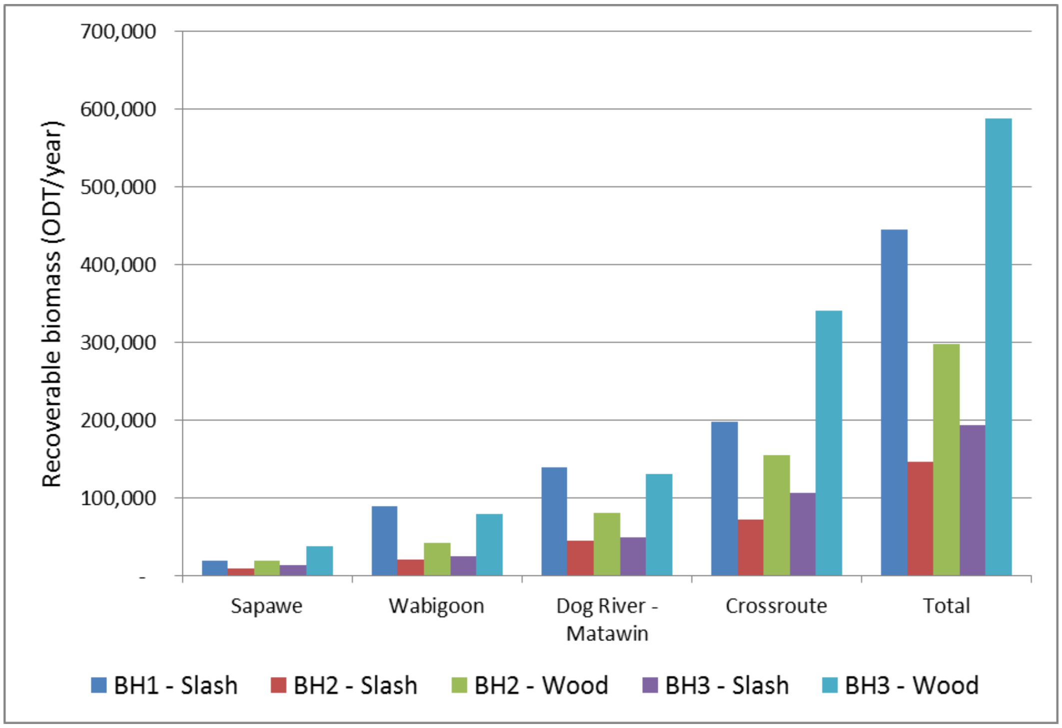


Figure 3. Amount of recoverable biofibre for the 4 FMUs, by harvesting scenario

2.2.2 Biofibre harvesting scenarios

There are several different potential sources of biofibre available in crown land forests that could be utilized for bioenergy. Traditionally, forests in Canada have been utilized for *traditional forest industry* and products including dimensional lumber, pulp and paper and other materials (i.e. oriented strand board). The typical source for these products are the trunks (bole) of softwood and some hardwood species. A bioenergy industry that utilizes forest-based biofibre to produce energy (electricity, heat or liquid fuels) could utilize a mixture of biofibre material. During the initial phases of this project, the Advisory Committee recommended analyzing different biofibre harvesting scenarios so comparisons could be made for the various biofibre material and harvesting processes. More specifically, there was interest in comparing the potential environmental impacts of collecting already available forestry slash compared to harvesting additional standing trees, and the potential environmental impacts of these options. As such, three biofibre harvesting scenarios were defined to reflect possible biofibre harvesting practices for the Atikokan case study as well as practices that could be of interest elsewhere in Canada.

The biofibre harvesting scenarios focus specifically on two main sources of biofibre — existing forestry slash and unmerchantable hardwood trees species (poplar and birch) — and two different methods to extract the hardwood species from the forest. Table 2 summarizes the three biofibre harvesting scenarios that utilized these two main sources of biofibre, along with the BAU scenario. It is assumed that in the two biofibre harvest scenarios (BH2 and BH3) where hardwood trees are harvested, it is this harvesting that drives an incidental harvest of softwood trees. There is also an assumption that this incidental softwood harvest is traded for hardwood through the pulp and paper industry since only hardwood biofibre is required for white pellet production and hardwood is less desirable for the pulp-and paper industry than softwood. Further details on these biofibre harvesting scenarios are summarized in Appendix A.

Table 2. Biofibre harvest scenarios defined in the LCA

Biofibre Harvest Scenario	Abbreviation	Purpose	Details
Baseline – Existing practice	**BH0** (Baseline - BAU)	To have a baseline scenario to compare against BH1, BH2 and BH3.	• Harvest levels are defined for the traditional forest industry and biofibre harvested is destined for lumber, pulp & paper, etc. • Harvesting rates are based on historical harvest rates from the four FMUs and are held constant through the 100-year planning horizon. • FMU-specific roadside slash burning is taken into consideration.[16]
Road-side slash recovery	**BH1** (Slash)	Provides a harvesting scenario that looks at utilizing <u>only</u> existing slash and does not require additional tree harvesting for bioenergy.	• Slash is sourced from available roadside slash defined in BH0. • Slash is used to produce brown pellets and hog fuel. • Approximately 85% of the slash from the harvest level defined in BH0 is considered technically and economically recoverable.
Hardwood trees processed into chips at forest roadside	**BH2** (Delimb-Debark-Chip (DDC))	Provides a harvesting scenario that looks at an *additional* harvesting of unmerchantable hardwood trees for bioenergy. Trees are delimbed, debarked and chipped at roadside.	• Biofibre is sourced from unmarketable or unmerchantable poplar and birch trees within regular harvesting operations • Overall average % utilization of AAC increase to 75% – % of hardwood AAC used increase approximately 61% compared to BH0 – % of softwood used AAC increases approximately 12% compared to BH0. This softwood is an incidental harvest necessary to harvest the hardwood[17] • Hardwood species harvested are delimbed, debarked and chipped at roadside • All slash from DDC operations are hauled from forest to pellet facilities for drying process. • Hardwood chips are hauled from forest to pellet facility to produce white pellets.

[16] Refer to Table 9 for more information on the percent of road-side slash being considered in this study

[17] A major assumption in this work is that the volume of incidental softwood harvested in BH2 and BH3 will be traded for the equivalent volume of hardwood with the pulp & paper industry. There is a further assumption that this hardwood traded with the pulp & paper industry is sourced within the same FMUs and is available through harvesting operations defined in BH0.

			• Road-side slash from traditional forest sector (BH0) is not utilized and it is assumed the slash is once again burned at the same percentages as defined in BH0.
Hardwood trees processed into logs at forest roadside and further processed at pellet facility	**BH3** (Tree stem)	Provides a harvesting scenario that looks at a *further additional* harvesting of unmerchantable hardwood trees for bioenergy. Trees are delimbed at roadside.	• Biofibre is sourced from unmarketable or unmerchantable poplar and birch trees within regular harvesting operations • Overall average % utilization of AAC increase to 75% – % of hardwood AAC used increases approximately 110% compared to BH0 – % of softwood AAC used increases approximately 19% compared to BH0 • All slash from delimbing operations are left at forest roadside. • Hardwood logs are hauled from forest to pellet facility. • Tree bark from hardwood is used in drying process in pellet facilities • Hardwood chips are used to produce white pellets • Road-side slash from traditional forest sector (BH0) is not utilized and it is assumed the slash is once again burned at the same percentage as defined in BH0.

2.2.2.1 Percent increase in AAC utilized

For both the BH2 and BH3 scenario, there is an increase in the overall % AAC utilization rates in both softwood and hardwood species. The biofibre harvest scenarios target, harvest and utilize the unmerchantable hardwood species (poplar and birch) for white pellet production and it is this hardwood harvesting results in an incidental softwood harvesting. As stated above, it is assumed this incidental softwood harvest is traded for an equal amount of hardwood from the pulp and paper industry.

Table 3, Table 4 and Figure 4 summarize the average percentage increase of the AAC used[18] for both the hardwood and the incidental softwood harvesting for the four FMUs and each bioenergy scenario. The main percentage increase is from the hardwood harvesting (approximately 110% average increase in BH3 compared to BH0), where the percentage increase in the softwood harvesting is significantly smaller (20% increase in BH3 compared to BH0).

[18] It is important to highlight that for the bioenergy scenarios, there is no increase in the size of the AAC of any FMU – only in the percentage of the AAC being utilized.

Table 3. Hardwood harvesting rates (% of AAC utilized)

FMU	Hardwood harvesting rates (% of AAC utilized)				% increase from BH0 to BH2	% increase from BH0 to BH3
	BH0	BH1	BH2	BH3		
Sapawe	N/A	39	68	95	74%	144%
Wabigoon	46	46	71	95	54%	107%
Dog River	N/A	42	72	95	71%	126%
Crossroute	56	57	82	95	44%	67%
Average	**51**	**46**	**73**	**95**	**61%**	**111%**

Table 4. Softwood harvesting rates

FMU	Softwood harvesting rates (% of AAC utilized)				% increase from BH0 to BH2	% increase from BH0 to BH3
	BH0	BH1	BH2	BH3		
Sapawe	N/A	74	86	94	16%	27%
Wabigoon	85	83	89	95	7%	15%
Dog River	N/A	78	89	94	14%	21%
Crossroute	83	83	91	95	10%	15%
Average	**84**	**80**	**89**	**95**	**12%**	**19%**

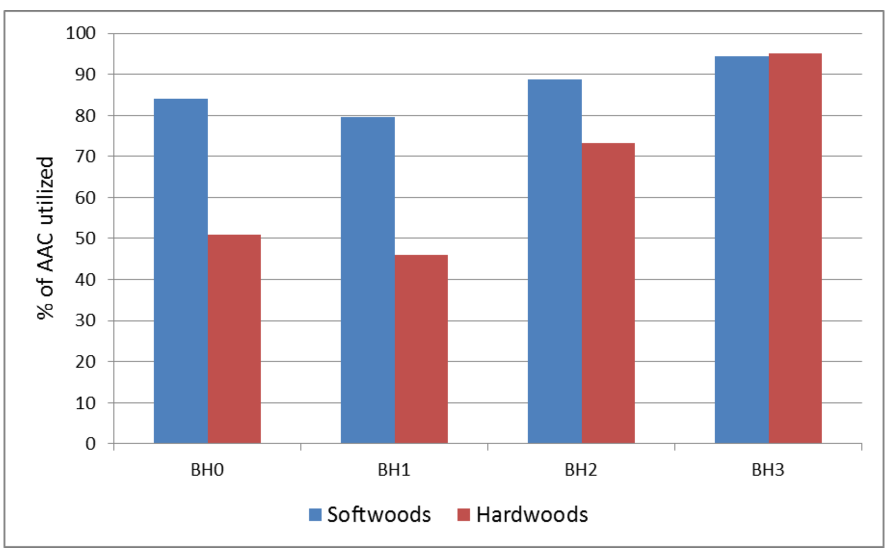


Figure 4. % of AAC utilized for the biofibre harvest scenarios

The total annual amount harvested and additional harvest area is as follows:

Table 5. Additional harvested area and volume harvested

Biofibre harvest Scenarios	Total Area harvested (ha/year)	Total volume of wood harvested (m3/year)
BHO	20,736	2,316,207
BH1 (Relative to BH0)	0	0
BH2 (Relative to BH0)	6,111	742,240
BH3 (relative to BH0)	11,899	1,468,589

This work is investigating the potential environmental impacts of increasing the harvest rate. It is important to remain cognizant that BH3, the highest projected harvest scenario, is 95% of the maximum AAC utilization. By definition, this rate of harvest is considered within Ontario forest management guidelines[19] which adhere to all biodiversity and sustainability requirements. This work is an evaluation of some of these metrics and should not be interpreted as a critique of Ontario's forest management plans. As well, the landscape-level results in this work are not compared to biodiversity requirements/thresholds in Ontario's sustainable forest management plans.

2.2.3 Forestry roads

There are two types of additional forestry roads required for the three biofibre harvest scenarios. For BH0, new permanent main roads are required to access the future planned harvest. Data provided by FPInnovations indicates that there is an additional 831 kilometers of main forestry road planned over the next 10-year and these roads are assumed to be permanent on the landscape. This information was used for the BH1 biofibre harvest scenario in the LCA analysis. For BH2 and BH3, new in-block (tertiary) roads are required to access and harvest the additional biofibre defined in each of these two bioharvest scenarios. Data provided by FPInnovations indicates that there is an additional 371 km / year of new tertiary roads required for BH2 and an additional 734 km / year of new tertiary roads required for BH3, and these roads are assumed to have a lifespan of 20 years before natural succession reclaims these roads. This information was also used for the BH2 and BH3 biofibre harvest scenarios in the LCA analysis.

2.2.4 Conversion scenarios

There are four conversion scenarios identified. These conversion scenarios will have different plant efficiencies. These conversion scenarios were strategically identified[20] and selected to cover a range of configuration scenarios to produce electricity: using white or brown pellet in 100% combustion scenarios, and co-firing pellets with coal. The final conversion scenario looks at utilizing hog fuel in a hypothetical CHP facility to produce both heat and electricity. These four different conversion scenarios are summarized in Table 6.

---

[19] http://www.appefmp.mnr.gov.on.ca/eFMP/home.do?language=en

[20] Internal EC report, *Bioenergy Scenario Development for Atikokan Supply Region*, Unpublished. Heather MacLean 2011

Table 6. Conversion scenarios defined in this LCA

Conversion scenario	Abbreviation	Purpose
100% white pellet combustion to produce electricity	C1	Represents a repowering scenario in retrofitted pulverized coal boiler at the Atikokan GS to produce electricity.
Co-firing with 65% white pellet and 35% coal to produce electricity	C2	Represents Canada's proposed coal-fired regulations[21]. Note this is a hypothetical scenario as Ontario regulations will not be allowed coal to be burned post 2015.
100% brown pellet combustion to produce electricity	C3	Represents a scenario that uses wood pellet made from roadside slash to produce electricity.
100% hog fuel combustion used in a hypothetical 50 MW_e CHP to produce electricity and heat	C4	Represents a scenario that uses unprocessed forestry slash to produce electricity and heat. Note this is a hypothetical scenario that involves a hypothetical CHP plant since the current Atikokan GS cannot process hog fuel. It is assumed there is an end user for the heat generated from the hypothetical CHP facility and that is not wasted.

2.2.5 Bioenergy scenarios selected

Table 7 and Figure 5 summarize the six bioenergy scenarios selected for this study. These six bioenergy scenarios were selected to provide an adequate range of plausible bioenergy scenarios that takes into consideration the different biofibre sources and conversion techniques.

Note that each bioenergy scenario utilizes different annual amount of biofibre and produces different annual quantities of electricity; however, the results in the work will be normalized to the functional unit defined in the LCA so a comparison can be made across all bioenergy scenarios and the fossil fuel reference case.

[21] Proposed regulation to Canadian Environmental Protection Act, 1999: Reduction of Carbon Dioxide Emissions from Coal-Fired Generation of Electricity Regulations (Canada Gazette, Vol. 145, No. 35) August 27, 2011 http://www.gazette.gc.ca/rp-pr/p1/2011/2011-08-27/html/reg1-eng.html

Table 7. Bioenergy scenarios defined

Bioenergy scenario	Biofibre harvest scenario	Conversion scenario	Biofibre amount utilized (ODT / year)			Coal amount (tonnes / year)	Electricity generated (MWh / year)	Generation Station Capacity Factor (%)
			Slash	White biofibre	Pellets / slash produced			
Scenario A - 100% white pellets using white pellets from hardwood chips	BH2	C1	55,623	296,896	296,896 white pellets	N/A	515,329	27%
Scenario B - 100% white pellets using white pellets from hardwood logs	BH3	C1	109,920	587,436	587,436 white pellets	N/A	1,019,625	55%
Scenario C - 65% co-fire using white pellets from hardwood chips and 35% coal	BH2	C2	55,623	296,896	296,896 white pellets	212,090	807,963	44%
Scenario D - 65% co-fire using white pellets from hardwood logs and 35% coal	BH3	C2	109,920	587,436	587,436 white pellets	419,640	1,598,628	86%
Scenario E - 100% combustion using brown pellets from slash	BH1	C3	443,936	N/A	377,345 brown pellets[22]	N/A	674,714	37%
Scenario F - hypothetical 50 MWe CHP using hog fuel	BH1	C4	157,863	N/A	157,863 hog fuel	N/A	315,100	54%

[22] It is assumed 15% of the biofibre slash is used in the drying process

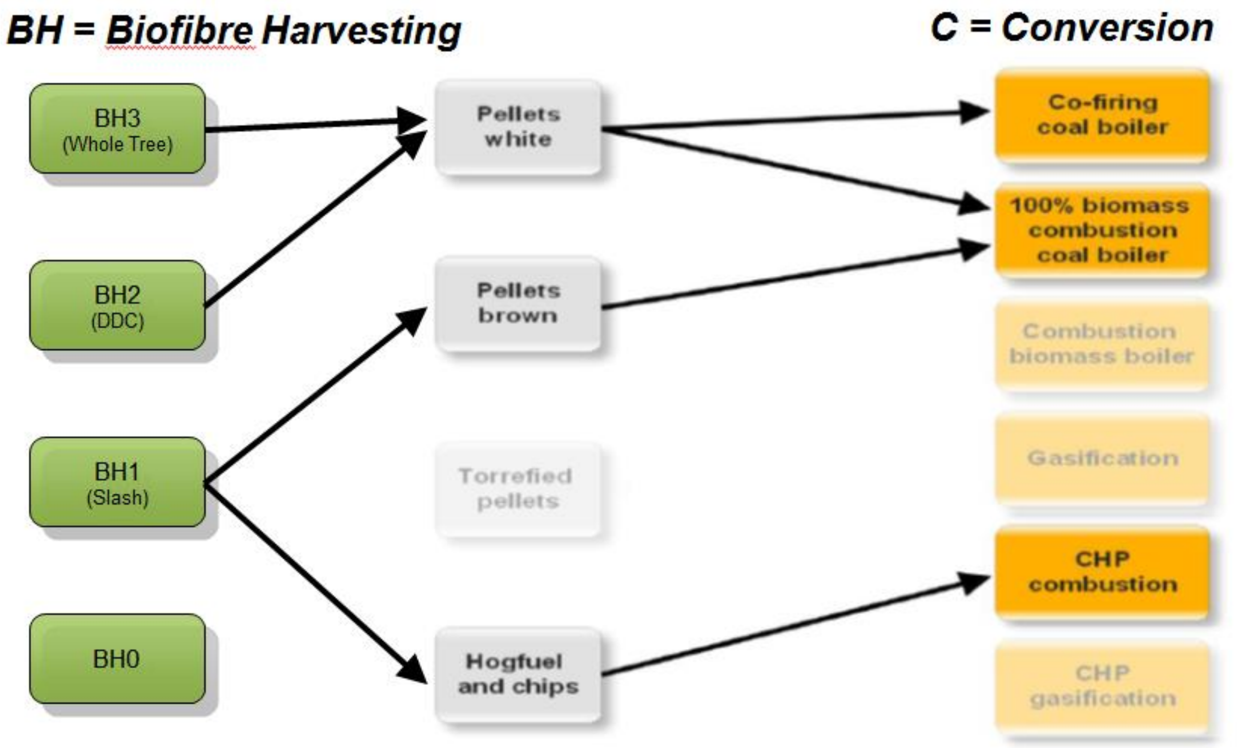


Figure 5. Visualization of bioenergy scenarios

Source: EC 2011

The bioenergy scenarios also include the activities and potential environmental impacts related to the burning of roadside slash defined in the BH0 biofibre harvest scenario. The coal reference case also includes the activities and potential environmental impacts related to the burning of roadside slash.

Table 8 summarizes what happens to the roadside slash considered in the bioenergy scenarios.

Table 8. Summary of fate of roadside slash piles for each biofibre harvest scenario

Scenario	Fate of BH0 Road-side slash
Bioenergy scenario A and bioenergy scenario C (BH2)	Road-side slash available in the BH0 baseline is not collected (the biofibre used for processing drying is taken from the new slash generated from the BH2 harvest levels) and is considered to be burned at the same percentage as the BH0 baseline. The new roadside slash that is produced from the BH2 harvest levels and remains at the roadside is considered not to be burned[23] and is left to decompose. When comparing bioenergy scenario A and Scenario C to the coal reference case, the potential environmental impacts from roadside slash burning are the same and therefore have no net effect.

[23] This is discussed further in Section 2.3.

Bioenergy scenario B and bioenergy scenario D (BH3)	Road-side slash from BH0 is not collected (the biofibre used for processing drying is taken from the bark of the hardwood logs harvested from the BH3 scenario) and is considered to be burned at the same percentage as the BH0 baseline. The new roadside slash that is produced from the BH3 harvest levels and remains at the roadside is considered not to be burned[24] and is left to decompose. When comparing bioenergy scenario B and Scenario D to the coal reference case, the potential environmental impacts from roadside slash burning are the same and therefore have no net effect.
Bioenergy scenario E and bioenergy scenario F (BH1)	Road-side slash from BH0 is collected for both process drying and pellets. When comparing bioenergy scenario E and Scenario F to the coal reference case, there will be a change related to the potential environmental impacts of roadside slash burning since the slash is now being taken and combusted at the pellet plant (for process drying) and GS (to produce electricity).

2.3 Forest carbon modelling and carbon accounting framework

A key component to understanding the carbon and GHG emission impacts of utilizing biofibre is to incorporate the dynamic nature of the forests. Forests can effectively contribute to GHG mitigation strategies by sequestering carbon in live trees, dead trees and soil. Equally, extracting biofibre to use in bioenergy applications (combustion of wood pellets to produce electricity or heat) can also result in GHG emissions. Of interest in this study is the relationships and tradeoffs seen with biofibre harvesting as it relates to forest carbon, and the net GHG emissions from this process. The work does not assume the often-stated carbon neutrality of biomass combustion, but rather incorporates and models the change in forest carbon with the traditional LCA GHG emissions to arrive at an overall profile of the GHG emissions using biofibre. The accurate accounting of carbon emissions from biofibre combustion and the concept of carbon neutrality was noted as one of the three significant environmental issues during the online research and survey of environmental and forest conservation organizations.[25]

This framework is summarized in Figure 6 below.[26] It is acknowledged that forest-based carbon accounting methodologies and frameworks is an active area of research and discussion. Choosing the most appropriate carbon accounting framework based on the conditions and policy mandate was beyond the scope of this project. The carbon accounting framework presented in this work is a similar framework that frames the GHG question from the perspective of “What GHG increases would the atmosphere see” as a result of utilizing and combustion biomass.

---

[24] This is discussed further in Section 2.3.

[25] Internal EC report, *eNGO and Conservation Group Outreach on Biomass*, Unpublished. The Pembina Institute, 2011

[26] Adopted from Chen, J., Colombo, S.J., Ter-Mikaelian, M.T., and Heath, L.S. “Carbon budget of Ontario’s managed forests and harvested wood products, 2001–2100.” *Forest Ecology and Management* 259 (2010): 1385–1398.

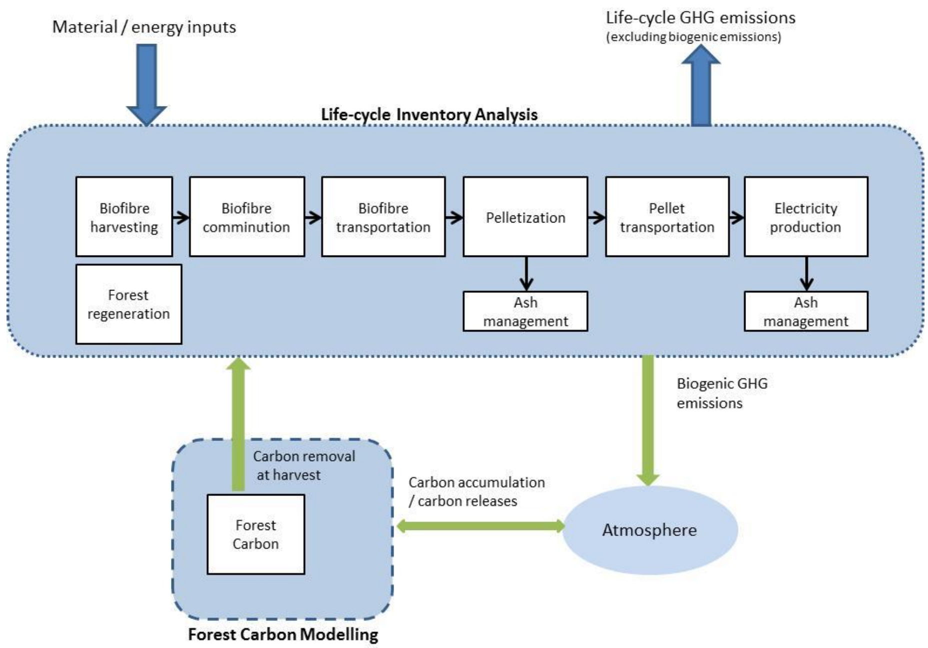


Figure 6. Framework for assessing total GHG emissions from forest bioenergy

The carbon modelling and estimation of the forest carbon stocks was completed by the Ontario Ministry of Natural Resource (OMNR) using the FORCARB-ON, an Ontario-specific adaptation of the FORCARB2 model[27]. FORCARB-ON is a large-scale forest carbon budget model that projects carbon stocks in forests and harvested wood products under different forest management scenarios. FORCARB-ON was selected for this work because it is the only existing large-scale forest carbon budget model parameterized for Ontario. For this work, FORCARB-ON models and quantifies the change in forest carbon stocks using FMU data (i.e. cutblock attributes, shape files, stand yield curves) and takes into account the continuous harvest rates and amounts for the biofibre harvest scenarios over the 100-year planning horizon. The forest carbon analysis estimates the carbon in each of the carbon pools every 5 years. The main data source for this modelling was a set of cutblocks scheduled for harvest for a 10-year period of the latest four FMU FMPs. This modelling and projections of forest carbon required establishing a future starting point and defining succession rules. The methodological details and approaches used in the modelling are summarized elsewhere.[28] The following paragraphs only briefly describe the methodology and modelling of the forest carbon.

In summary, cutblocks were rolled forward to 2015 to correspond with the modelling timeframe; no natural succession or disturbances were applied to these cutblocks as they were rolled forward. In the baseline scenario, carbon stocks were estimated taking into account forest growth in areas harvested in biofibre harvest scenarios BH2 and BH3 relative to biofibre harvest scenario BH0. Thus, the effect of BH2 and BH3 scenarios on forest carbon stocks includes changes in the forest that would take place had this forest not been harvested. Projected forest

[27] Chen, J, “Future carbon storage in harvested wood products from Ontario’s Crown forests,” *Canadian Journal Forest Research*, 38 (2008): 1947 – 1958; DOI: 10.1139/X09-046

[28] Internal EC report, *Estimating forest carbon stocks for wood pellet production scenarios,* Unpublished. Michael Termikaelian, Ontario Ministry of Natural Resources, February 2012

growth included natural disturbance (at the rates defined by respective FMP) and successional changes.

To simulate forest growth in this modelling, three sets of succession rules (post-disturbance, natural succession and post-harvest succession) and multiple rules for each successional type were applied. It is important to note that the science on the effects of harvest on medium and slow soil carbon pools is evolving and more detailed and precise methodologies may be available in the future to include these effects in an LCA. For this project, soil carbon pools following harvest were held constant (at pre-harvest level) unless tree species composition of post-harvest stand differs from that of pre-harvest stand. Details and justifications for this approach are captured in the supporting modelling documentation.[29]

The FORCARB-ON model and additional modelling / analysis completed in this project quantifies the following carbon pools:

- Carbon in live trees (both above- and below-ground parts of the tree)
- Carbon in dead trees (both above- and below-ground parts of the tree)
- Carbon in Downed Woody Debris (DWD)
- Carbon in the soil
- Carbon in the forest floor
- Carbon in understory vegetation
- Carbon in roadside slash
- Carbon in black carbon[30]

Road-side slash and slash pile burning

Under the BH0 biofibre harvest scenario, a certain amount of roadside slash is considered to be openly burned. Road-side slash generated from full-tree and DDC operations are typical in the management operations in Northwest Ontario FMUs. Road-side slash burning was considered an important activity to include in this work because of the environmental emissions that are released during the process, particularly air emissions. Including carbon in roadside slash in the overall forest carbon analysis is also important to capture the loss of carbon as a result of this activity; this provides a more accurate quantification of the net GHG emissions when considering other biofibre harvest scenarios relative to this BH0 baseline.

Estimating the carbon stocks in slash pile burning required estimation of several parameters including the amount of carbon that is consumed during burning, the rate of slash pile burning variance between the different FMUs, the decay rates of slash piles left unburned and the rate of black carbon produced during slash pile burning. There was no information on the decay rates of slash piles, so estimations based on the decay rates of CWD were used as a basis and adapted. Data availability to estimate these parameters was limited and the approaches taken to estimate all of these important parameters are fully captured in the supporting modelling documentation.[31]

---

[29] *Estimating forest carbon stocks for wood pellet production scenarios*

[30] Black carbon is considered a byproduct of incomplete combustion of biofibre and is considered a stable form of carbon that remains throughout the planning horizon as it is resistant to further biological or chemical degradation.

[31] *Estimating forest carbon stocks for wood pellet production scenario*

Table 9 summarizes the data collected and used to estimate the rate of slash pile burning.

Table 9. Summary of data used to estimate rate of slash pile burning

Forest Management Unit	Total harvest area (ha)	Total area covered with slash piles (ha)	Total area cleared due to slash pile burning (ha)	Rate of slash pile burning (%)
Crossroute Forest (2004-2009)	62,442	1,998	378	19
Dog River-Matawin Forest (2002-2003, 2007-2009)	30,785	985	489	50
Sapawe Forest (2005, 2007, 2008)	3,020	97	21	22
Wabigoon Forest (2005, 2007-2009)	17,953	575	313	55
Average area cleared due to slash pile burning (%)			**32.9%**	

Some further important assumptions were used to model the slash pile burning:

- Of the slash piles that are burned:
  - It is assumed that 85% of the carbon contained in these slash is burned with a very small percentage of carbon being converted to black carbon.
  - When converting the forest carbon results to GHG emissions, this carbon is assumed to be converted to CO_2.[32]
  - It is assumed that the remaining 15% of the carbon in the slash piles does not burn, and this carbon decays at a defined rate.
- For the BH2 and BH3 harvest scenario, it is assumed that the additional roadside slash that is generated through the increased harvest remains at roadside and is not burned, but is left to decompose. This assumption was made based on the fact that the small historical rate of slash pile burning reflects the operational capacity of forest companies to burn this roadside slash and burning any of the additional slash is considered unrealistic.
- It is assumed that dry biofibre contains 50% carbon by weight.

2.4 Coal reference case

The Atikokan GS currently uses lignite coal from the Bienfait mine in southeast Saskatchewan, approximately 3 km southeast of the town of Bienfait. The coal is processed and shipped by rail to the Atikokan GS.

[32] In reality, there will be other GHG emissions other than CO_2 but to simply the calculations, all carbon was assumed to be converted to CO_2.

It was attempted to model and quantify the coal reference case as closely as possible to the open-pit mining processes from the Bienfait mine. However, due to information and data limitations, collection of operational information and data on environmental releases specific to the Bienfait mine was limited. Therefore, data was collected from a variety of public sources (NPRI, Greenhouse gas reporting website) and similar open-pit surface mines located within Saskatchewan and Alberta. Some of the mining information collected was from sub-bituminous coal where the coal extraction processes are similar to the strip-mining techniques used at the Bienfait mine.

The reference case used in this study should therefore be considered a more generic coal reference case using the different data sourced gathered through the coal research sub-project. For details on the coal mining sites researched, data sources and assumptions used to develop a coal reference case for this LCA, refer to the separate report provided through the coal sub-project.[33]

Coal was selected as the main fossil fuel reference case for this work, as opposed to natural gas, because coal data and information was required for co-firing bioenergy scenarios C and D. Also, project timelines and data collection priorities did not accommodate including a natural gas reference case. Although the current plan is for coal to be phased out in Ontario by 2014, it still represents a reasonable reference case for this first iteration work.

The temporal boundary of the coal reference case is 100 years (2015 to 2115) and was chosen to align with the temporal boundary of the bioenergy scenarios, which represents an adequate timescale of a full forest management cycle. Under the reference case, it is assumed that the Atikokan GS will generate electricity using coal and the annual electricity generated will be constant over the planning horizon.

When presenting the potential environmental impacts of the coal reference case, it is important to note that the environmental impacts associated with slash pile burning (defined in the BH0 biofibre harvest scenario) are also included in the definition of the *reference* case and are included in the results. It is dually important to note that, because of data limitations, the potential environmental impacts associated with tree harvesting in the BH0 baseline are <u>not</u> included in any of the bioenergy harvest scenario or the coal reference case results. This is because the BH0 harvest rates are the same for every bioenergy scenario and the reference case and are not attributed to the bioenergy or reference case scenarios.

[33] Internal EC report, *Coal-to-electricity reference case – Bienfait lignite coal mine operations,* Thomas Marr-Lang, 2012.

3. LCA methodology, approach and potential environmental impacts

3.1 Introduction

Life cycle assessment (LCA) is a step-wise quantitative approach to model the potential environmental impacts of a product throughout its life cycle. This study aims to assess the potential environmental impacts of biomass-derived electricity using ISO's framework which are outlined in ISO 14040 and 14044.[34] The LCA process includes several recursive steps including: goal and scope definition, inventory analysis, impact assessment, interpretation and report writing (conclusions, limitations and recommendations). The ISO step-wise process is displayed in Figure 7 below.

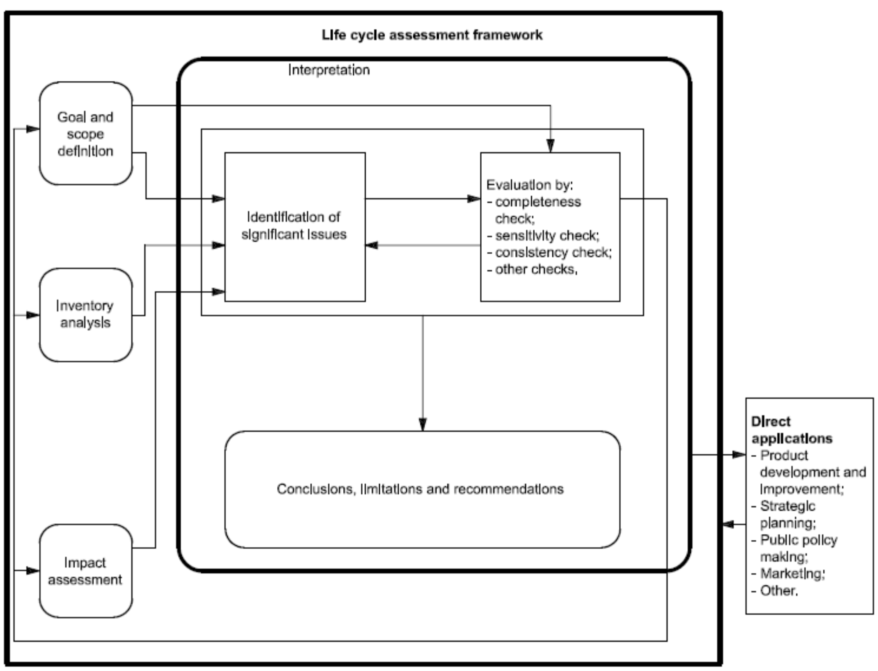


Figure 7. ISO step-wise process

As mentioned, the goal of this study is to estimate the potential life cycle environmental impacts of using forest-based biomass to generate electricity at OPG's Atikokan generating station, and

[34] ISO, "Environmental Management - Life Cycle Assessment - Principles and Framework," in *ISO 14040:2006(E)*, ed. ISO (2006).

compare to a coal reference case. Another objective is to compare bioenergy scenarios to understand the relative impact of changing biofibre harvesting or combustion scenarios. For example, understanding the relative potential environmental impacts of utilizing available harvest slash compared to harvesting hardwood trees will be very insightful.

3.2 Research, methodology and selected LCA approach

3.2.1 Air, hydrology and soil environmental considerations

A review of specific literature on the production of electricity and heat from biomass showed no consensus on or preference for the application of a specific LCIA method. Few studies explored beyond the GHG inventory and assessed selected environmental impact categories. The wider selection of environmental impact categories in one study[35] reflects the complete use of the comprehensive environmental impacts list covered by the LCIA method (Ecoindicator 99). This comprehensive approach was used in assessing which potential environmental impact categories are most sensitive for this project.

The following paragraphs present a brief summary of the main studies reviewed:

Life Cycle Assessment of Fossil and Biomass Power Generation Chains, Bauer (2008)

- focus of the evaluation of total GHG emissions in terms of CO_2-equivalents: CO_2, NO_X, SO_2, Particulates (PM2.5)
- Ecoindicator 99 for a large array of end point impacts: carcinogenics, respiratory inorganics, radiation, ecotoxicity, land use, fossil fuels, climate change, ozone layer, acidification, eutrophication, minerals

Life Cycle Assessment of Wood Pellet Use in Ontario's Nanticoke and Atikokan Generating Stations, Zhang et al. (2009)

- GHG emissions associated with pellet production and transportation
- forest carbon accounting

Life Cycle Assessment in the Bioenergy Sector: developing a Systematic review, Rowe et al. (2008)

- biomass for heat and power: data collected included primary energy input (MJ), energy output (MJ) and GHG output (g CO_2 equivalents) for each process step of each chain.
- the energy and GHG data were converted into standard units, and the energy requirement (MJ input / MJ output) and GHG output were calculated.

Life Cycle Assessment of Burning Different Solid Biomass Substrates, Itten et al. (2011)

- LCIA - Ecological Scarcity 2006.
- emissions into air: benzene, particles, nitrogen oxides, methane, lead, dinitrogen oxide, cadmium, dioxin, sulphur oxide, NMVOC and fossil CO_2.
- emissions into soil: heavy metals

[35] Bauer, C. (2008) *Life Cycle Assessment of Fossil and Biomass Power Generation Chains.* An analysis carried out for ALSTOM Power Services. PSI-Report No.08-05. Paul Scherrer Institut, Villigen PSI, Switzerland.

- GHG, quantified into GWP by IPCC 2007, 100a.

A Streamlined Life Cycle Analysis of Canadian Wood Pellets, Bi (2008)

- energy use inventory
- GHGs inventory: CO_2, CO, CH_4 , N_2O, NO_X, VOC, PM, SO_X, Aldehyde, NH_3
- ozone depletion, smog, acid rain and health impact (no mention of the LCIA method used)

Life Cycle Assessment of Bioenergy Systems - Comparing Greenhouse Gas Emissions of Power Generation with Biomass to Fossil Energy, Jungmeier, (2004)

- Results: GHG emissions

Regarding hydrology, many studies also identify the potential for forest harvesting to substantially alter sediment load and water yields. However, these impacts are considered minimal in this LCA as all harvesting scenarios fall below the Annual Allowable Cut (AAC) set by the Ontario Ministry of Natural Resources (OMNR). The AAC that has been determined by OMNR is expected to adequately account for all non-timber values (including water quality), and critical Equivalent Clearcut Area thresholds are unlikely to be exceeded. Therefore, increases in turbidity resulting from the increased hardwood harvest activities are not anticipated to introduce significant risk to environmental values. As outlined in one study,[36] further uncertainty in the potential for forest harvesting to substantially increase water yields results from the considerable water storage effects in these large watersheds. Studies have shown that understanding the magnitude of these hydrological effects requires detailed knowledge of the basin's size, climate, vegetation, topography, geology and soils.

Increased nutrient loading and resulting freshwater eutrophication of surrounding water courses (i.e. streams, lakes) represents the main impact of concern expected from forest harvesting for biomass production, and which may also be addressed through conventional LCA approaches.

In summary, the majority of the reviewed biomass LCA studies presented mainly a LCI of GHG, NO_x, SO_x, and PM emissions into the environment. Given the range of parameters identified, the most quantified environmental impact category is usually climate change. In order for an LCA study to address a wider range of potential environmental impact categories through LCIA, a larger array of data supporting the complexity of the LCIA methodology is needed. Based on the limited number of emissions quantified by the reviewed studies, most of these did not require a complex LCI structure.

Besides climate change, Bauer (2008) quantified a larger number of potential environmental impact categories related to biomass combustion through the LCIA method Ecoindicator 99. The LCI data was obtained from the Ecoinvent database.

Currently, Ecoinvent[37] is the world leading inventory database supporting the complexity of a full LCA study, including selection of multiple project-oriented environmental impact categories. Generally, for the LCA studies performed at a higher level of complexity, with a wide selection

[36] Buttle JM, Creed IF, Moore RD. 2009. Progress in Canadian forest hydrology, 2003 – 2007, *Canadian Water Resources Journal* 34: 113-126

[37] Ecoinvent, http://www.ecoinvent.ch/

of relevant environmental impact categories, such as in the case of this analysis, the use of Ecoinvent is essential. LCA practitioners recognize that the processes inventoried and quantified in Ecoinvent are geographically specific. However, as complex LCI data is needed for a full LCIA, the practice of adjusting the Ecoinvent processes and emissions to more site-specific, local conditions has been largely accepted by the LCA community.

Regarding the selection of a specific LCIA methodology, currently there is no consensus on the "best" approach. Each LCIA method has its own characteristics, depending on implemented science, modeling practice, characterization of environmental impacts as midpoints or/and endpoints, definition of characterization factors, etc. The choice of a specific LCIA has to be adapted to the needs of the project, from definition of the most relevant impact categories to the selection of temporal perspectives.

The LCIA method selected for the current project is ReCiPe 2008.[38] The ReCiPe LCIA methodology is considered as being the most suitable choice based on the following justifications:

- The selection of environmental impact categories quantified by ReCiPe covers to the best extent the environmental impact categories suggested by the Advisory Committee, while addressing the most sensitive environmental impacts specific to the project.
- The current project, as a first iteration, addresses the selected potential environmental impact categories at the midpoint level, and specifically targets midpoints which converge to the ecosystem quality endpoint category. Most of the existing LCIA methods convert emissions into impact categories at midpoint level (i.e. acidification, climate chance, ecotoxicity) while others employ impact category indicators at the endpoint level (such as human health and damage to ecosystem quality). It is desirable that LCIA methods be harmonized at the level of detail where the results are provided for both the mid- and endpoint impact categories from elementary emissions, and quantitative links are provided between the midpoint and endpoints themselves.
- ReCiPe offers such harmonization, by providing results both at midpoint and endpoint level. The initial LCI data can be quantified through midpoint equivalence factors into midpoint categories, while the same LCI data can be directly quantified through endpoint equivalence factors into endpoint categories. The strength of ReCiPe resides on the fact that a direct connection can be established between the midpoint and endpoint categories, resulting in a seamless flow of data starting from LCI, through midpoint categories, to endpoint categories.
- To a certain extent, Impact 2002+ offers the seamless connection from midpoint to endpoint. However, the available selection of potential environmental impact categories in Impact 2002+ is narrower than what is offered by ReCiPe, while the list of environmental emissions used to quantify the ecotoxicity (a complex environmental topic) is also narrower.
- Future iterations of the project, following this first iteration, will be able to use the same data needs and structure established during the current iteration to quantify, if desired, the environmental impacts at damage level (endpoint).

[38] ReCiPe, http://www.lcia-recipe.net/. The version of ReCiPe used in this work is 2008 and the version of the Ecoinvent database used is V2.2 (2010)

- Many of the midpoint environmental impact categories in ReCiPe have a strong component oriented towards ecotoxicity in the environment, which can be further elaborated at endpoint as ecosystem quality.
- Ecoinvent offers excellent data coverage for use of ReCiPe.
- ReCiPe comes with free technical material from the developers of the method.

3.2.2 Non-traditional LCA environment considerations

A review of literature was also conducted to ensure that the methodology adopted in this LCA incorporated potential environmental impacts critical to soil nutrient cycling and forest productivity, biodiversity and wildlife. Information from this research review was valuable in formulating approaches to include these non-traditional LCA impacts.

Past studies[39] indicate that biomass harvesting primarily affects soil nutrient loadings through increased release from forest slash material spread on site. Soil nutrient impacts may be accounted for in conventional LCA methodologies, however alternative methodologies such as Millennium Ecosystem Assessment (MEA).[40] LCA offer the benefit of incorporating a wider range of environmental indicators as well forecasting soil carbon levels. Yet, significant knowledge gaps in northwest Ontario do exist surrounding the potential harvest impacts on long-terms soil productivity and nutrient cycling. For the MEA approach to be applied to this LCA analysis, it would require more granular soil data from the FMUs under study. Currently, the MEA methodology had soil data available only by eco-regions and the eco-region in Northwest Ontario completely covers the landbase in this work. Because of these significant data gaps, soil nutrient and forest productivity was not investigated or researched in this work.

An important component of biomass sustainability is the maintenance of biological diversity over time which is largely dependent upon ecosystems' resilience to perturbation events — in other words, the ability to endure periodic disturbance or change and maintain the critical components that enable process and function to continue. Given the obvious complexity of *biodiversity* as an attribute, this work should focus on key ecological components that may detect changes in natural biological diversity as exemplified by potential changes in the area of forest type by seral class, structure and intactness, for example.

One approach outlined[41,42] is a theoretical method to quantify land occupation and generic characterization factors for local species diversity in Central Europe. While the approach offers much value, the characterization factors are based on the highly altered ecosystems of Europe which contrast sharply with the Boreal forest in Ontario. Another drawback to the approach is that it may not be effective at discerning key differences between competing indicators and is

---

[39] Rosie Saad, Manuele Margni, Thomas Koellner et al., "Assessment of land use impacts on soil ecological functions: development of spatial differentiated characterization factors within a Canadian context", *International Journal Life Cycle Assessments* (2011), 16:198-211

[40] Millennium Ecosystem Assessment, http://www.maweb.org/en/index.aspx

[41] Thomas Koellner, Roland Scholz, "Part 1: An Analytical Framework for Pure Land Occupation and Land Use Change", 2007 *International Journal of LCA 12 (1): 16-23*

[42] Thomas Koellner, Roland Scholz, "Part 2: Generic Characterization Factors for Local Species Diversity in Central Europe", 2008 *International Journal of LCA 13 (1): 32-48*

dependent on rare species and species occurrence inventories that are not generally available in this area.

A biodiversity sub-report prepared for EC identifies that "Biodiversity is not only important in terms of composition, but also in relation to structure and function. That is, biodiversity is not merely a list of what is present. Further, biodiversity also refers to the variety of plants, animals, and fungi at three scales—genes, communities, and landscapes."[43] McCavour et. al. highlights that current empirical data gaps are significant and limits recommendations based on qualitative assessments of impacts across four phyletic groups: understory plants, fungi, saproxylic invertebrates, and vertebrates.

Consequently, challenges exist for incorporating these impact categories into existing LCA frameworks. However, at the landscape level, three main themes from the literature do emerge in terms of potential biodiversity impacts:

- the maintenance of coarse woody debris (CWD)
- the relative abundance of old seral dominated vegetation
- the fragmentation of natural ecosystems

In addition, community indicators (such as a representative amphibian species) can be specifically selected because their performance is considered sensitive to changes in critical processes and functions important to much of the wildlife community. For example, leopard frog is a faunal indicator that occurs in the forests of northern Ontario and in the vicinity of the selected coal mine in Saskatchewan.

Aside from the adaptation of traditional LCA methodology frameworks to include a greater range of relevant ecological indicators, a potential improvement to the LCA process may be provided through the use of GIS data products. Insight from GIS information is expected to provide added value to the LCA process as it is commonly employed for wildlife and biodiversity assessments, and is deemed scientifically defensible. Also, the existence of useful GIS datasets across the globe offers the spatial transferability of the assessment between sites, and datasets can be incorporated within large multi-stakeholder cumulative effects assessments.

This work therefore focuses on a landscape-level approach and key indicators that will detect changes in natural biological diversity as exemplified by potential changes in selected indicator species abundance and distribution that are autocorrelated to forest age, structure and intactness. Despite the limitation and assumptions of the proposed methodology, there was agreement among the Advisory Committee there is value in completing the landscape-level approach.

3.3 LCA scope

A significant focus of the LCA lies in modeling realistic activities that are local to the Atikokan region. This includes forest harvesting methods and equipment, transportation, pelletization and combustion at the Atikokan facility, as well as activities related to coal extraction, processing,

[43] Internal EC report, *The effects of forest harvest residue removal on biodiversity in northwest Ontario with special reference to the hardwood component.* Unpublished. M.J McCavour et. al, 2011.

transportation and combustion at the Atikokan facility. This study identified datasets where local data was not available or has a high degree of uncertainty.

3.3.1 Description of pathways

As described in Section 2.2.5, this LCA study evaluated the following scenarios:

1. Scenario A: BH2 + C1 (Nonmerch chips + 100% white pellets)
2. Scenario B: BH3 + C1 (Nonmerch logs + 100% white pellets)
3. Scenario C: BH2 + C2 (Nonmerch chips + 65% white pellets)
4. Scenario D: BH3 + C2 (Nonmerch logs + 65% white pellets)
5. Scenario E: BH1 + C3 (slash + 100% brown pellets)
6. Scenario F: BH1 + C4 (slash + hypothetical CHP)
7. Scenario Coal: coal from open pit mining in western Canada

Detailed descriptions of biofibre harvest (BH) scenarios and conversion (C) scenarios are given in Sections 2.2 and Section 0, respectively.

3.3.2 Functional unit

LCA is structured around a functional unit which defines the product of interest that is being studied. It is an equivalent unit of output among competing scenarios (when comparing among options). Potential environmental impacts, where feasible, are scaled relative to that functional unit. The functional unit for this analysis is 1 MWh of electricity generated.

3.3.3 Boundary selection

Each scenario represents a fuel pathway that can be broken down into discrete steps that are termed “activities”. Examples of activities include the raw material extraction, fuel combustion, and the transportation of products from point A to B. Activities are then presented in the form of a “system activity map” which gives a snapshot of all activities in one scenario that are required to deliver an end product.

Boundary selection is the practice of identifying the activities that will be quantified in the study. A simplified activity map is provided in Figure 8 below and detailed activity maps are included in Appendix B for each scenario. The activities presented in Figure 8 show the major operational activities at a high level.

Bioenergy scenarios

At a simplified level, the activities included within the scope are presented in Figure 8 below and include commissioning, biomass harvesting/forest regeneration, pelletization (for bioenergy scenarios A to E) and combustion. Other sub-activities that feed into these processes (i.e. upstream fuel production, ash management) were included in the analysis but for simplicity are not displayed in Figure 8. The geographical boundary for the biomass scenarios includes the four FMUs (where biomass is harvested), pellet plants, the Atikokan GS, road network used in the scenario and the landfills where ash is disposed.

Coal scenario

The activities included in the coal life cycle scenario include the open-pit coal mining, transportation by rail to the power plant and combustion of the coal at power plant. The geographical boundary of the coal scenario includes the Bienfait coal mine in Saskatchewan and the rail transportation from Saskatchewan to the Atikokan GS.

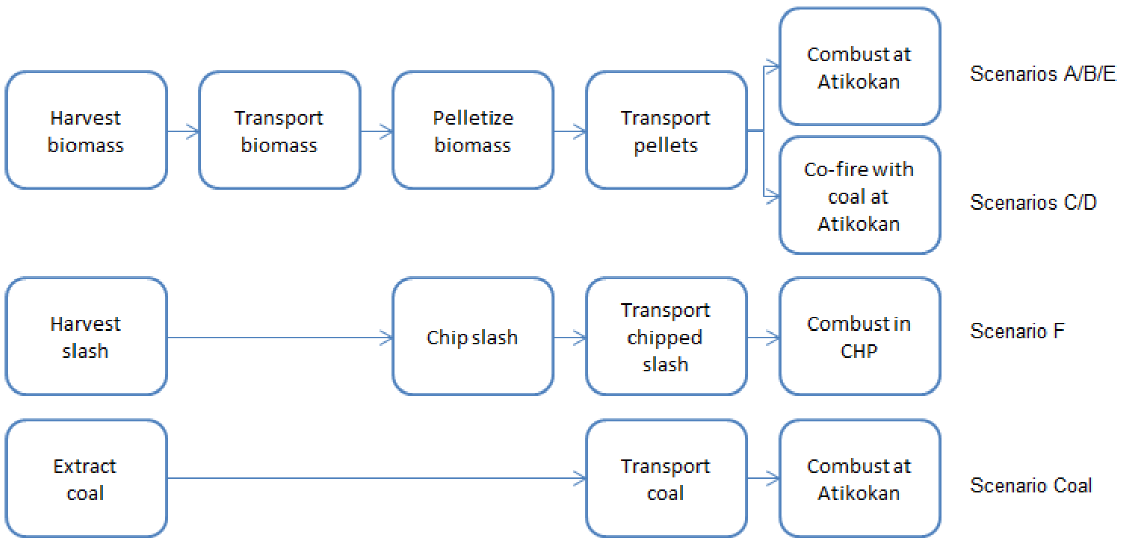


Figure 8. Simplified activity map for all bioenergy and coal reference case scenarios

3.3.4 Cut-off criteria

Cut-off criteria are used to identify activities that will have a relatively small impact on the final LCA results. This study used the following principles to determine which activities to include and which to exclude.

1. **Relative mass, energy or volume** – If the activity requires an insignificant amount (mass, volume or energy) of material or fuel relative to the whole then the input is excluded. In this case we assumed significance as >1% of total material mass, volume or energy input to the life cycle. Any material input less than 1% was not included.

3.3.5 Temporal boundary selection

The temporal boundary is 100 years, starting with the first year of biofibre harvest.[44] This timeframe is appropriate to capture both the short-term and long-term potential environmental effects from biofibre harvesting.

[44] The start date for this analysis, including the carbon modelling, is 2015. This is considered a reasonable date considering the target date of 2014 for coal phase-out. The 2015 start date was also chosen to simplify the work of rolling forward the forest modelling for both the carbon modelling and FPInnovations work.

3.3.6 Allocation procedures

Allocation was applied in two places within the study:

1. **Forestry slash at roadside** – In harvesting of softwood and hardwood trees using a full tree or DDC harvest methods, trees are skidded to the roadside where the limbs and tops of the trees (slash) are removed. The slash is used in bioenergy scenarios scenarios E and F as a feedstock for brown pellets and hog fuel respectively. This study attributed a portion of the potential environmental impacts of the harvest, skid, processing and silviculture activities to the slash using a mass balance. Also, because new forestry roads are planned and required for the BH0 harvest levels, this study also attributes a portion the potential environmental impacts for the construction of these main forestry roads.[45]
2. **CHP** – The hypothetical CHP facility in bioenergy scenario F produces both heat and power where the other scenarios produce only power. Recall that all scenarios should be compared using the common functional unit of 1MWh of electricity. Comparing the CHP results with other scenarios in terms of electricity alone would be an unfair and inconsistent comparison because the cogeneration unit produces more products. To make a fair comparison, the hypothetical CHP facility was analyzed in the following ways:
    i. the CHP scenario was "modified" where electricity is generated on first pass at 23.7% electrical efficiency. Residual heat is produced at 47.9% heat efficiency and is recognized as a valuable co-product. The heat is given credit by assuming it is equivalent to a theoretical amount of electricity and this is calculated by multiplying the CHP heat output by 23.7%. The overall electrical efficiency of the "modified CHP" case is 35.1%. It is recognized that generating heat from the residual CHP heat would in reality, have a lower efficiency than 23.7%.This methodology was derived in consultation with EC and the Advisory Committee during the project.
    ii. the environmental impacts in the CHP scenario were equally divided among the product outputs on an energy basis and this study excluded the impacts attributed to the heat generation. The decision to allocate and not to perform a system expansion is in keeping with the objectives of this study which focuses biomass used for power generation, and was guided by the Advisory Committee.

3.3.7 Critical review

ISO 14040/14044 recommends a critical review when making comparative assertions between project options that will be disclosed to the public. The project team retained an external critical reviewer to ensure that the data, assumptions and decisions in this project are consistent with ISO principles and not biased by the project team or the Advisory Committee. The critical review process was executed concurrently with the project with reviews performed at several project milestones. The critical review reports are included in Appendix I.

In addition, this LCA was supported by the participation of an Advisory Committee. The Advisory Committee reviewed important project documents and methodology throughout the project and more in-depth discussions were held with sub-committees when detailed discussion was required. For example, committee members were involved in detailed discussions to

[45] Refer to Appendix C for the summary notes from the discussion and decisions regarding Allocation.

determine suitable biodiversity and wildlife indicators, allocation methodology and further defining combustion scenarios.

3.4 Life cycle inventory (LCI)

The life cycle inventory (LCI) stage of this LCA aimed to quantify the potential environmental releases (e.g. CO_2, NO_x, SO_2 and heavy metals) of all seven scenarios. This process was performed for each activity defined in the activity map and used a combination of production data and emission factor data.

Production data included information such as biofibre mass harvested from the FMUs or distance from the FMUs to the pellet plant. This information was collected through previous subproject documentation and active research. The mass and energy flows were modelled for each activity that is displayed in the activity maps.

The environmental releases of each activity were estimated using emission factors from similar processes. This project modelled the scenarios as closely as possible to conditions that are expected in northwest Ontario and thus placed a higher value on emission factors derived from the subprojects already completed. When local data was not available, datasets were augmented with similar processes from other sources such as Ecoinvent, NREL and other published research papers.

The environmental releases were quantified for each activity and summed for each of the seven scenarios. The result is a quantitative estimate of environmental releases that can be used in a comparative analysis comparing project options. The environmental releases quantified were then fed into the LCIA process and contributed to defined midpoint categories, discussed in Section 3.5.

The LCI was completed using the following frameworks:

- ISO 14040, 14044 Environmental management — Life cycle assessment — Principles and framework
- National Inventory Report 1990–2009: Greenhouse Gas Sources and Sinks in Canada
- 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Land Use
- IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories
- Life Cycle Assessment – Inventory Guidelines and Principles - EPA 1993

The LCI outputs an environmental release (i.e. emissions) summary for each scenario. The next stage (LCIA) converted these emissions into potential environmental impacts.

3.5 Life cycle impact assessment (LCIA)

The LCIA phase of an LCA is the evaluation of potential environmental impacts of the resources used and emissions identified during the LCI. An LCIA attempts to establish a linkage between the product or process and its potential environmental impacts. Although much can be learned about a process by considering the LCI data, an LCIA provides a more meaningful basis to make comparisons. By using science-based characterization factors, an LCIA calculates the impacts the environmental emissions have on selected environmental impact categories.

3.5.1 Potential environmental impact categories

ISO 14040-14044 standards outline the mandatory elements of an LCIA. They include:

1. Selecting impact categories;
2. Classifying LCI results; and
3. Characterizing LCIA results

3.5.1.1 Selecting potential environmental impact categories

Impact categories reflect the issues of environmental relevance that result from environmental releases calculated in the LCI. For example, SO_2 emissions by themselves are not an impact category but the effects of SO_2 emissions (i.e. acid rain) will result in increased acidification for soils and surface water.

The first key step in LCIA is to select the potential environmental impact categories that will be considered in this study. There are a number to choose from and they include:

- **Ecological impact categories** — global warming, depletion of stratospheric ozone, acidification, eutrophication, photochemical smog, ecotoxicological impacts (terrestrial and aquatic toxicity)
- **Human health impact categories** — toxicological impacts, non-toxicological impacts, impacts in work environment
- **Resources impact categories** — energy and material, land, water

The initial focus of the LCIA was to identify the significant potential environmental impacts that occur during the entire life cycle of production of electricity from biomass and coal. To date, no scientific consensus has been reached regarding which impact categories should be considered significant for the production of electricity and heat from biomass. Additionally, there are often limitations with respect to data and equivalence factors that render the exercise of limited value.

Based on the review of available LCA studies of electricity and heat production from biomass and the inputs from the Advisory Committee, the following potential environmental impact categories were considered as being significant and relevant to biomass:

- Climate change
- Terrestrial acidification
- Freshwater eutrophication
- Terrestrial ecotoxicity
- Freshwater ecotoxicity
- Natural land transformation
- Fossil resource depletion

These seven potential environmental impacts are defined midpoints in the ReCiPe methodology that converge to the ecosystem quality endpoint.

Health impacts due to air emissions from combusting biomass and coal for electricity/heat production are extremely important, especially when one considers the different possible air emissions from these sources (carbon monoxide, particulate matter (PM), NO_x, SO_x, heavy metals).[46] Particulate matter (PM), specifically, may be an important environmental impact for bioenergy scenarios E and F from the perspective of slash piling burning. With this *first iteration* LCA focusing on midpoints that will converge to the ecosystem quality endpoint and PM emissions at the facility being very specific to technology implementation, the PM midpoint as indication of health impacts was not included in this work.

The environmental impact categories mentioned above are typical for the traditional LCIA methods. Given the importance of the potential non-traditional LCA environmental impacts given the context of the current project, the following additional potential environmental impact categories not covered by any of these existing LCIA methodologies were selected:

- Age (Seral) class distribution
- Coarse woody debris distribution
- Fragmentation

These additional environmental impacts are a novel approach in this work, standing apart from the traditional LCIA and ISO14040-14044 processes.

Discussions with the Advisory Committee revealed agreement on the first two potential environmental impacts — age class distribution and coarse woody debris. Some concern, however, was expressed regarding the quantification of biodiversity impacts associated with fragmentation. It was pointed out that fragmentation can actually create vectors that increase the quantity of species, and it is possible that this would not necessarily be harmful. While this is indeed possible, it is unlikely that linear fragmentation from anthropogenic development such as roads will improve native species diversity. The literature is consistent in identifying the increased potential for ecosystem degradation as a result of increases in the potential for invasive species introduction; in sediment and nutrient deposition in streams and rivers from crossings; and in consumptive pressure from an increase in human access. Two experts in this field of study were contacted directly: Dr. Brad Stelfox and Dr. Sarah Jordaan, co-authors of a published study[47] assessing the utility of fragmentation as an important metric for consideration in Life Cycle Analysis in the hydrocarbon sector of Alberta. Both of these scientists agreed that fragmentation measured as linear edge density would be a useful metric and that the approach to quantify it for this project is a reasonable and worthwhile approach.

Table 10 summarizes the selected potential traditional and non-traditional environmental impacts.

Table 10. Potential environmental impact categories

Environmental Impact Category	Description	Equivalent Unit	Primary Impact
Traditional environmental impact categories			

[46] A. Demirbas, "Hazardous Emissions from Combustion of Biomass." *Energy Sources, Part A,* 30:170-178, 2008

[47] S. Jordaan, D. Keith, B. Stelfox, "Quantifying land use of oil sands production: a life cycle perspective", Environmental Research Letters (2009), 024004

Climate change	Release of greenhouse gases contributing to climate change	kg CO_2 equivalent to air	Air
Terrestrial acidification	Precipitation containing high concentration of sulfuric and nitric acids	kg SO_2 equivalent to air	Soil / Land
Freshwater eutrophication	Nutrient enrichment of the aquatic environment	kg PO_4^{-3} to freshwater	Water
Terrestrial ecotoxicity	Toxic environmental releases that affect terrestrial ecosystems (i.e. heavy metals)	kg 1,4-DCB equivalent to soil	Soil / Land
Freshwater ecotoxicity	Toxic environmental releases that affect freshwater ecosystems (e.g. heavy metals)	kg 1,4-DCB to freshwater	Water
Natural land transformation	Land transformed from natural state	m^2 natural land transformed	Land use change
Fossil fuel depletion	Consumption of non-renewable resources	kg crude oil	Resources
Non-traditional environmental impact categories			
Age (seral) class distribution	Area of forest age class structure. A measure of forest canopy structure	hectares of age class[48] by forest type[49]	Biodiversity
Coarse woody debris (CWD)	Amount of CWD. A measure of forest ground structure	m^3 of CWD / hectare by forest type	Biodiversity
Fragmentation	Linear edge density of roads. A measure of intactness	km (linear edge) / km^2 forest	Biodiversity

3.5.1.2 Classifying LCI Results

The purpose of classification is to organize and combine the LCI results (inputs and outputs as emissions) into the impact categories defined (for example, classifying carbon dioxide emissions to the climate change impact).

The emissions from the processes described in the activity maps for electricity production from biomass were inventoried and grouped according to the potential environmental impact categories selected.

The emissions factors were selected and aggregated in accordance with the LCIA method. The emission factors were also grouped into environmental categories and subcategories. Such classification addresses, besides the category of the environmental impact (to air, water, soil), more elaborate concepts given the susceptibility of certain emissions to have a higher impact in

[48] Age class is defined as tree species within certain ages, i.e. 0-20 years, 21-40 years, 41-60 years, etc. To keep results manageable, four main age class categories were selected for this this analysis: 0-20 years (early age class), 41-60 years (medium age class), 121-140 years (early-old age class) and 141+ years (old age class).

[49] The forest types for this analysis are a subset and combination of the forest unit information from the FPInnovations work. The classifications of forest types are Lowland conifer, Upland conifer, Hardwood, Mixed wood and White/Red Pine.

environments with different geographic, social and ecological characteristics (high population density, low population density, etc.).

3.5.1.3 Characterizing LCIA Results

Characterization is the process of modelling the LCI results within midpoint impact categories using science-based conversion factors (for example, modelling the potential impact of carbon dioxide and methane on climate change). Characterization provides a direct way to compare the LCI results within each impact category, by translating different inventory inputs into directly comparable impact indicators.

The midpoint impact indicators were characterized using the following formula:

$$\sum \textit{(Inventory data x characterization factor) = Environmental impact indicator}$$

It is recognized that Canadian LCA practitioners currently use European or American methodologies when conducting comprehensive impact assessments, despite the fact that these methods may not be specifically constructed for use in Canadian studies. Due to the lack of suitable models currently available, work is being undertaken to develop a Canadian LCIA methodology by adapting existing LCIA models to the Canadian context. Since Canadian or site-specific factors are not yet available, generic ReCiPe factors were used. However, the LCA model was designed to accommodate further changes of the emission parameters and equivalence factors, as the Canadian-specific factors become available.

Figure 9 below presents the selected environmental impact categories and the connection between midpoint and endpoint environmental impact categories in ReCiPe.

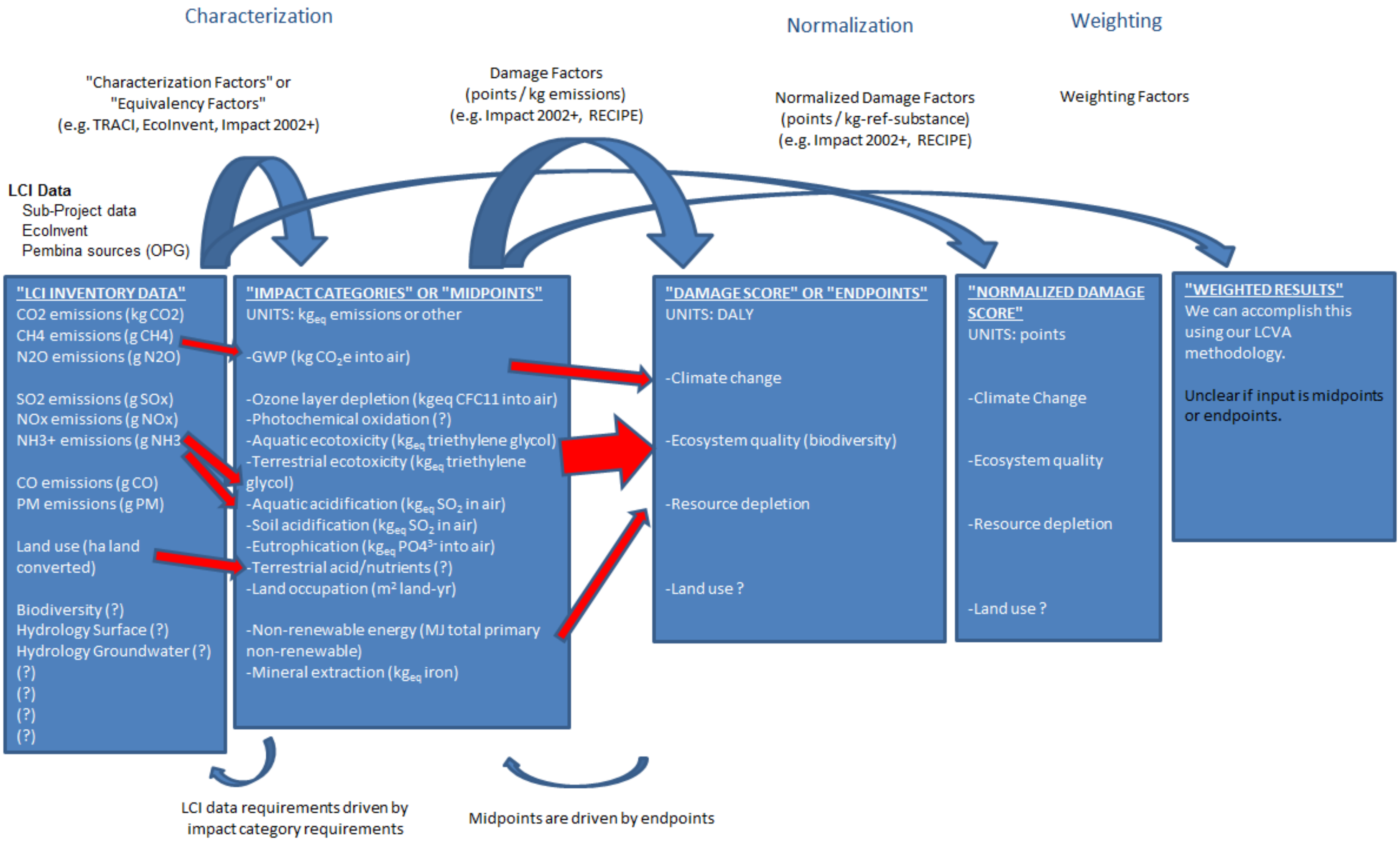


Figure 9. Overall LCA approach and ReCiPe approach

3.6 Overall modelling framework

The overall modelling framework is composed of two approaches to model the potential traditional and non-traditional environmental impact categories and is displayed in Figure 10 below.

The traditional environmental impact categories (orange highlighted boxes below) are modelled using a combination of Ecoinvent's life cycle inventory database, ReCiPe's LCIA methodology, OMNR's forest carbon modelling and data from the other sub-projects.

The non-traditional environmental impact categories (green highlighted boxes below) are novel impact categories and not covered by any existing LCIA methodologies. These impact categories were modelled separately from the traditional impact categories using a GIS modeling platform.

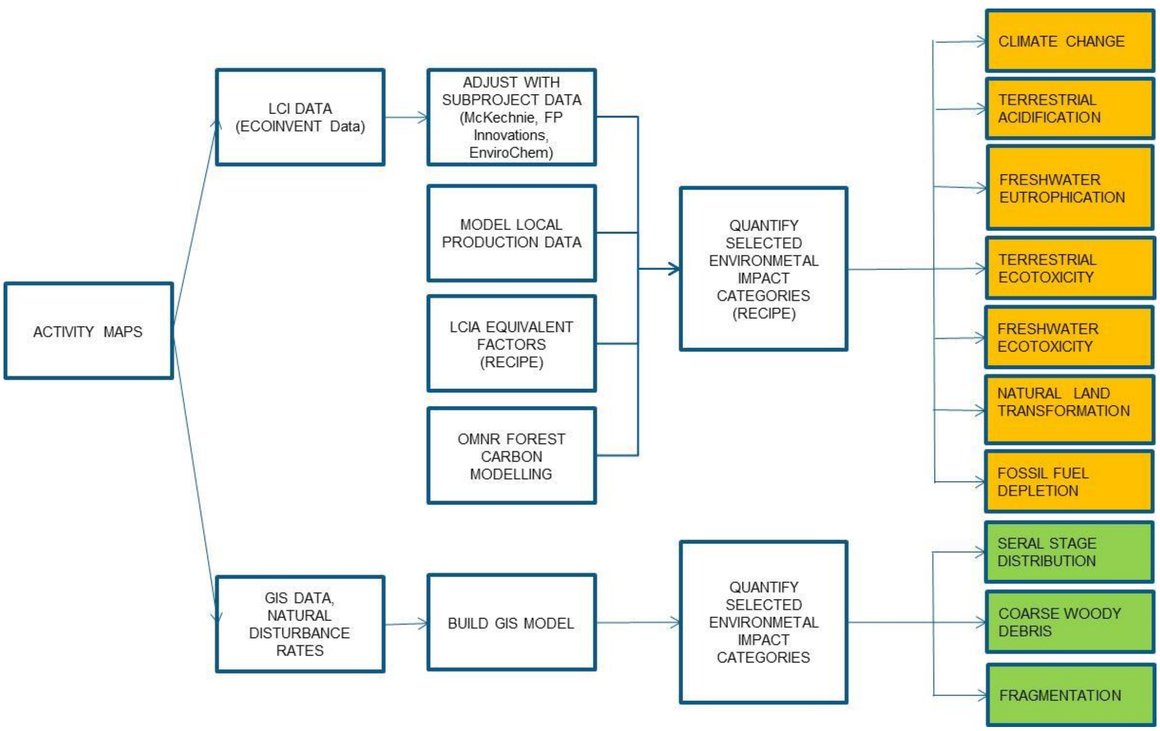


Figure 10. Conceptual model for quantification of potential environmental impacts

3.7 LCA data sources

The LCA models local Northern Ontario conditions as closely as possible and uses a variety of data sources to quantify results for each scenario. A higher emphasis was placed on datasets that had geographical or technological similarities to our project conditions. In addition, EC has also commissioned a number of separate research projects that have generated useful data. Finally, generic European datasets (i.e. Ecoinvent processes) were necessary when localized factors were not available.

The process for creating the model can be described as follows:

1. Model the seven scenarios using Ecoinvent LCI processes and ReCiPe's LCIA midpoint characterization factors.
2. Overwrite or "proxy" Ecoinvent emission factors using data from other sub-projects (i.e. McKechnie, FP Innovations, EnviroChem, coal research, landscape-level GIS data).
3. Overwrite Ecoinvent environmental release factors using data from other local datasets (i.e. Ontario electricity grid factor).
4. Select other data (pellet production levels, power production, transportation distances, transportation methods) using local information.

Figure 11 shows a high-level summary of these data sources. Details on the other major data sources used in this modeling can be found in Appendix H.

Biomass

	Climate Change	Terr. Acid.	Freshwater Eutroph.	Terr. Ecotox.	Freshwater Ecotox.	Nat Land Trans.	Fossil Fuel Depl.	Seral Dist	CWD	Fragment
Harvest	FPI						FPI		Landscape Level SP	
Transport pellet plant	McKechnie						McKechnie	N/A	N/A	N/A
Pelletize	McKechnie						McKechnie	N/A	N/A	N/A
Transport power plant	McKechnie						McKechnie	N/A	N/A	N/A
Combustion	McKechnie						McKechnie	N/A	N/A	N/A
Ash disposal	McKechnie						McKechnie	N/A	N/A	N/A

Coal

	Climate Change	Terr. Acid.	Freshwater Eutroph.	Terr. Ecotox.	Freshwater Ecotox.	Nat Land Trans.	Fossil Fuel Depl.	Seral Dist	CWD	Fragment
Extraction				Coal SP					Landscape Level SP	
Processing				Coal SP					Landscape Level SP	
Transport power plant				Coal SP				N/A	N/A	N/A
Combustion	McKechnie	NPRI	NPRI	NPRI	NPRI		McKechnie	N/A	N/A	N/A
Ash disposal	McKechnie							N/A	N/A	N/A

Local data available
EcoInvent and other sources
N/A Not quantifying in 1st iteration

Ontario power grid modeled using EC NIR and NPRI

Figure 11. LCA data sources

FPI - FPInnovations report
McKechnie – McKechnie report
Coal SP – Coal subproject
Landscape Level SP – Landscape-level biodiversity subproject

3.8 Data quality

This project integrates datasets from a variety of sources including localized data obtained through sub-projects and generic data from Ecoinvent. Data quality assessment is an important step as results will only be as good as the data they are derived from. For this reason, it is important that data meets a minimum and consistent benchmark.

Ideally all the data that is used in the model will have the following characteristics:

1. **Temporally representative**– Has been published recently.
2. **Geographically representative**– Representative of the intended geographical area.
3. Technology representative – Representative of similar technologies to those being modelled.
4. **Comprehensive** – Includes releases for a wide variety of environmental impact categories and upstream/downstream processes.
5. **Transparent** – The source of the data is transparent, reputable and easy to verify.
6. **Accurate** – High degree of confidence that data is precise and accurate.

An assessment of these quality indicators is included in the Uncertainty Assessment and can be seen in Section 6.1.

3.9 Landscape-level modelling

The ALCES® modeling platform was chosen to simulate forest harvesting over the 100-year planning horizon and to forecast indicator performance. ALCES® is a computer model that can simulate and account for natural disturbance, ecological processes and land-use disturbances occurring on a regional scale over a period of time into the future; it has been deployed successfully around the world. The model has been peer reviewed in Canada for a number of purposes including in the LCA context. Jordaan et. al.[50] utilized ALCES® to quantify land use implications of oilsands development in northern Alberta compared with natural gas extraction in southern Alberta from a life cycle perspective.

The harvest block sequence beyond the first 10 years as forecast in the FMPs for the study area was not available. Harvest sequencing in an operational sense is dependent upon a large number of variables and the criteria are subject to change over a full rotation as market forces, natural disturbance, social and economic objectives and non-timber value constraints and targets often fluctuate. However, for strategic level systems dynamics assessments such as this study, a generic harvest queue rule can be applied. For the purposes of this analysis, the model was required to harvest the oldest eligible stands in each FLB in each year until the harvest target for each profile was satisfied. The consistency of this harvest queue algorithm is also helpful for the analysis because it does not introduce noise in the results due only to changing harvest sequences between scenarios as is likely if a relative oldest first or random harvest queue were used.

[50] S. Jordaan, D. Keith, B. Stelfox, "Quantifying land use of oil sands production: a life cycle perspective", Environmental Research Letters (2009), 024004

For a complete discussion and information on the modelling details and assumptions used to quantify the landscape level biodiversity impacts, refer to the report that accompanies the landscape-level modelling.[51]

3.9.1 Seral stage distribution

For analysis of seral stage distribution, forest is classified into 20-year age classes that are tracked explicitly on an annual basis. Change in age is brought about through harvesting or natural disturbance (includes fire, insect and disease perturbation). It is worth noting that while a constant rate of natural disturbance is provided by OMNR, the application of this disturbance in the simulation is not age dependant. This factor along with artifacts associated with 20-year age classes likely contributes to the periodic "jaggedness" of the seral stage area forecasts.

3.9.2 Forest fragmentation

Edge is forecasted to be created by all linear features, newly harvested cutblocks and burned areas. Permanent roads contribute edge throughout the entire forecast and include highways, powerlines, pipelines and permanent secondary access roads including forestry main haul roads. In-block (tertiary) haul roads associated with BH2 and BH3 incremental harvesting are assumed to have a lifespan of 20 years – after which it is assumed that forest regeneration reclaims these features from the landscape. Similarly, edge from cutblocks and burned areas is assumed to persist only for the first 20 years following harvest, after which it is assumed that successful regeneration has eliminated perceptible stand edge.

The GIS data provided has been compiled using Planning Composite Inventory (PCI) data rather than the Forest Resource Inventory (FRI). While FRI is based upon the interpretation of recent aerial photos, the PCI is an earlier FRI rolled forward to the year of the most recent FMP. When this rolling forward process takes places, not all recent depletions are included in the PCI and roads is one of those depletions. As a result, the current active road inventory is not fully represented in the data used. Figure 12 shows the current active road inventory used for this analysis overlaid on recent Google Earth imagery within the study area.

[51] Internal EC report, *An Assessment of Key Landscape Components as a Supplement to the Life cycle Analysis Expertise for Bioenergy Production Project*, Unpublished. The Silvatech Group, 2012.

Figure 12. Road Inventory (red) compared with Google Earth Imagery

Source – Google Earth

It appears that not all active roads are identified in the inventory and therefore the fragmentation associated with current roads should be considered conservative.

3.9.3 Coarse woody debris (CWD)

A common theme of key metrics for assessing landscape-level biodiversity emerged across all phyletic groups and was noted in biodiversity report prepared for EC:[52] the amount of CWD, the level of stand structure and the fragmentation of natural ecosystems. Further, CWD is an important functional and structural component of forested ecosystems.[53]

CWD is defined in various ways in the literature and in application by managers and practitioners. One study used the term to describe all states of dead wood in the cycle[54], from standing snags to logs and fallen branches. Others[55,56,57] have defined CWD as downed woody material, distinguishing it from the 'snag' or standing dead component. Two more studies[58,59] define CWD to include sound and rotting logs, snags and stumps generally greater than 8 – 10 cm in diameter.

[52] Internal EC report, *The effect of forest harvest residue removal on biodiversity in northwest Ontario with special reference to the hardwood component*, Unpublished. McCavour, McNair, Tittler, Gervais, Solarik, Greene, Messier

[53] Harmon et al. 1986

[54] Ibid

[55] Lofroth 1993

[56] Steventon 1994

[57] Province of British Columbia 1995

[58] Pedlar et al. 2000

[59] Stevens, 1997

Considerable information has been amassed concerning CWD dynamics in coastal forests of western North America and deciduous forests throughout the U.S., but relatively few studies exist from boreal Canada.

Sturtevant et al. describes CWD as including both downed and standing material and identified an important structural attribute – that CWD is composed of two distinct components, decay and accumulation stages. This report describes a “U-shaped” relationship between CWD and stand age that is composed of the decay of residual debris following harvest disturbance, followed by the accumulation of debris from the regenerating stand. In general, debris levels tend to be high following the initial stand disturbance. Residual (decay) debris then declines over time, with little additional input from the regenerating stand. As the stand matures, tree mortality due to competition and small-scale disturbance (i.e. windthrow) contributes to the CWD reservoir (accumulation). Debris levels usually peak during a transitional stage as the even-aged stand senesces into a more uneven age structure[60].This U-shaped temporal pattern has been observed in a number of other studies including northern hardwood forests,[61] wave-regenerated balsam fir forests,[62,63] lodgepole pine forests,[64] Douglas-fir forests[65] and Douglas-fir-western hemlock forests.[66] Other local studies[67] have not been able to identify an alternative predictive function of CWD relating to stand age and so for the purposes of this first iteration assessment, the functional relationship described by Sturtevant et al. is used as the basis for predicting CWD based on forecasted stand age. Figure 13 describes this relationship conceptually.

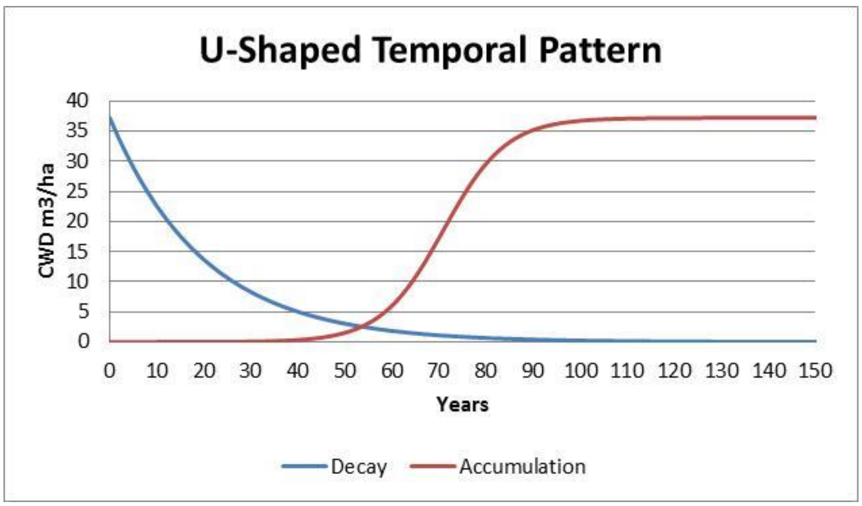


Figure 13. Conceptual relationship between CWD and stand age

[60] Sturtevant et al, 1997

[61] Tritton 1980

[62] Lambert et al. 1980

[63] Lang 1985

[64] Romme 1982

[65] Spies et al. 1988

[66] Agee and Huff 1987

[67] Ter-Mikaelian et al., 2008

For this analysis, individual models for each Forest Land Base (FLB) across each harvest scenario were developed using area-weighted forecasts of slash remaining in the cutblock following harvest.[68] This slash data is important because the information takes into account the different harvesting systems forecast to be applied to the various ecosystems across the range of harvest scenarios. Further, these models enable the temporal forecasting of CWD to be calculated by FLB across scenarios according to the age class distribution of the entire forested landscape and for that to be broken down into its component parts (decay and accumulation). It is also important to note that the CWD accounting is only relevant to the FLB types (merchantable timber types) and does not report CWD in other ecosystems (i.e. treed swamps). This is not reported on as it is assumed this is the same in all scenarios. The forecasting only enables an assessment of the components on the merchantable land base and relative to BH0.

[68] The forecasted amount of slash remaining in the cutblocks after full-tree, DDC and CTL harvesting systems was provided by FPInnovations.

4. Potential environmental impacts of bioenergy scenarios compared to coal reference case

This chapter summarizes the potential environmental impacts for each bioenergy scenario in relation to the coal reference case. The absolute potential environmental impacts for each bioenergy scenario and the coal reference case are summarized in Appendix D.

It is important to note that these are relative to the BH0 baseline scenario — meaning that only the potential environmental impacts associated with *additional* activities from BH0 are accounted for and quantified. For BH1, the additional activities include the removal and processing of roadside slash (where a portion of the roadside slash was considered to be burned in BH0). For BH2 and BH3, the additional activities include the incremental harvesting, processing and transportation of hardwood and softwood trees above the defined BH0 utilization rates.

The potential environmental impacts in the ReCiPe framework are expressed in the LCA functional unit MWh. Due to complexity of the three landscape-level impacts and time limitations, these impacts were not expressed in the LCA functional unit MWh. Furthermore, the environmental impacts for BH2 and BH3 are quantified relative to BH0, and not the coal reference case because of data limitations and the challenges of quantitatively comparing environmental impacts between a landbase in Northwest Ontario and a generic Western Canada open-pit mining coal operation. A qualitative discussion on the environmental impacts of forestry compared to coal mining is provided in Section 4.4.5.

Since there are different upstream activities for the coal reference case and the bioenergy reference case, categories were developed in order to facilitate the comparisons between the coal reference case and the bioenergy scenarios. These categories are summarized in Table 11.

Table 11. Main LCA categories developed to facilitate comparison

Category	Coal Reference Case	Bioenergy Reference Case
Commissioning	Commissioning activities	Commissioning activities – pellet plant construction, retrofit of the Atikokan GS and construction of main and tertiary forestry roads.
Fuel Procurement	Coal mining, processing and transportation	Biofibre harvesting, comminution, forest regeneration, transportation of biofibre from forest to pellet plant, pelletization, ash management, transportation of pellets to power plant
Coal combustion	Environmental releases associated with coal combustion	N/A
Power Plant	Fuel handling, ash management	Fuel handling, biofibre combustion, ash management

4.1 General observations – by environmental impact

Sections 4.1.1 to 4.1.10 draws some initial general observations on the potential environmental impacts quantified, and the general trends that are observed. These sections summarize at a high-level the changes. Section 4.2 provides more details and justification for the change in potential environmental impacts.

Table 12. Symbol definition

Symbol	Meaning
ReCiPe environmental impacts	
	No significant change ± 5%
	Increase in potential environmental impact (negative impact) from coal to bioenergy scenario. Size of arrow proportional to increase.
	Decrease of potential environmental impact (positive impact) from coal to bioenergy scenario. Size of arrow proportional to decrease.
Landscape-level environmental impacts	
	Increase in potential environmental impact (negative impact) from BH0 to biofibre harvest scenario. Size of arrow proportional to increase.
	Decrease of potential environmental impact (positive impact) from coal to bioenergy scenario. Size of arrow proportional to decrease.
	Increase in potential environmental impact from BH0 to biofibre harvest scenario that does not reflect a positive or negative impact. Size of arrow proportional to increase.

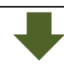
⇩	Decrease in potential environmental impact from BH0 to biofibre harvest scenario that does not reflect a positive or negative impact. Size of arrow proportional to increase.

4.1.1 Climate Change

To facilitate the inclusion of the time-dependent component of the *forest carbon* component in the climate change environmental impact, the average GHG emissions (tonnes CO2e / MWh) over the 100-year planning horizon has been combined with the LCA GHG emissions. . For a more detailed discussion on the quantification of the GHG emissions related to forest carbon, refer to Section 4.3.

Table 13 summarizes the change to the potential environmental impact climate change (tonnes CO_2eq / MWh)

Table 13. General trend for potential environmental impact climate change, relative to coal[69]

Bioenergy scenario	Change (relative to reference case)	Main contributors to change	Further Discussion
Bioenergy scenario A		No significant change. Increased GHG emission intensity from forest carbon component similar magnitude as GHG emission intensity of coal	GHG emission intensity from forest carbon (from harvesting standing trees) is similar intensity as coal.
Bioenergy scenario B		Small reduction in GHG intensity from forest carbon component	Small GHG intensity benefit from forest carbon (harvesting more biofibre). Less impact based on % utilization of additional forest units and age class of these target stands.
Bioenergy scenario C		No significant change	GHG emission intensity from forest carbon (from harvesting standing trees) is similar intensity as coal.
Bioenergy scenario D		Small reduction from forest carbon component	Small GHG benefit from forest carbon (harvesting more biofibre). Less impact based on % utilization of additional forest units and age class of these targeted stands.
Bioenergy scenario E		Reduction from forest carbon component	Significant GHG reduction intensity from sourcing roadside slash.
Bioenergy scenario F		Reduction from forest	Significant GHG reduction intensity from sourcing roadside

[69] Climate change results presented here include the GHG emissions from the forest carbon component.

		carbon component No further pellet processing of biofibre	slash

For all scenarios, the forest carbon component is time-sensitive and the 100-year average value has been used.

For full-tree harvesting for bioenergy (bioenergy scenarios A, B, C and D), all potential climate change impacts show a minor change in the average GHG emission intensity, compared to coal, over the 100-year planning horizon. This result is primarily because of the inclusion of the forest carbon component in the GHG accounting and the carbon implications from harvesting standing trees. Bioenergy scenarios E and F show a significant reduction in the potential climate change impact compared to coal, primarily because this resource will naturally decompose if not utilized and a percentage of the roadside slash is being burned in the baseline scenario.

4.1.2 Terrestrial acidification

Table 14 summarizes the change to the potential environmental impact terrestrial acidification (kg SO_2eq / MWh)

Table 14. General trend for potential environmental impact terrestrial acidification, relative to coal

Bioenergy scenario	Change (relative to reference case)	Main contributors to change	Further Discussion
Bioenergy scenario A	⬇	Coal combustion produces high NOx/SO2 emissions from coal combustion	SO2e releases from coal combustion are approximately 10 times larger than biomass combustion.
Bioenergy scenario B	⬇	Same as above	Same as above
Bioenergy scenario C	↓	Same as above	Similar to above, but changes are less significant because co-firing with coal.
Bioenergy scenario D	↓	Same as above	Same as above
Bioenergy scenario E	⬇	Same as above	Same as above
Bioenergy scenario F	⬇	Same as above	Same as above

The coal pathway has higher emissions of terrestrial acidifying substances than any of the biofibre pathways. Coal combustion is the largest contributing stage in the life cycle and contributes 94% of SO_2e emissions to the life cycle total. The combustion of pellets contributes 52% of the pellet life cycle pathway (for Scenario A). The next largest sources of SO_2e in the bioenergy scenarios' life cycle are the pellet plant (25% of bioenergy scenario A's life cycle) and the biofibre recovery (18% of bioenergy scenario A's life cycle). The emission factors used to calculate the coal combustion SO_2e emissions are quite robust drawing upon data from Atikokan's operations which was obtained through NPRI. The SO_2e pellet combustion emission factors are taken from Envirochem's Task 5 report[70] that represents the current understanding of biomass combustion in Canada. The Envirochem Task 5 report was prepared for Environment Canada and summarizes the current state of literature at the time of this report.

4.1.3 Freshwater eutrophication

Table 15 summarizes the change to the potential environmental impact freshwater eutrophication (kg Peq / MWh)

Table 15. General trend for potential environmental impact freshwater eutrophication, relative to coal

Bioenergy scenario	Change (relative to reference case)	Main contributors to change	Further Discussion
Bioenergy scenario A	↓	Lignite coal extraction	Phosphate emissions at lignite mine from management of coal tailings. Environmental release factors taken from Ecoinvent.
Bioenergy scenario B	↓	Same as above	Same as above
Bioenergy scenario C	↓	Same as above	Similar to above, but changes are less significant because co-firing with coal
Bioenergy scenario D	↓	Same as above	Same as above
Bioenergy scenario E	↓	Same as above	Same as above
Bioenergy scenario F	↓	Same as above	Same as above

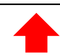
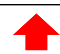
[70] Task 5 results were obtained through personal communication (email) with Sebnem Madrali on March 7, 2012.

The coal extraction activity is the main contributor to the difference in freshwater eutrophication and is driven by the release of phosphates to water. Phosphates are also released during the bioenergy scenario's pellet life cycle mainly from electricity consumption in the pellet manufacturing process. Both of these main contributors are calculated using Ecoinvent emission factors. The Ecoinvent lignite mine is based on European data that has limited document information and will likely not accurately reflect Western Canada mining conditions. Data information for phosphate releases was requested from the coal research subproject; however, phosphate releases from three separate Canadian lignite mines was not reported or mentioned.

4.1.4 Terrestrial ecotoxicity

Table 16 summarizes the change to the potential environmental impact terrestrial ecotoxicity (kg 1,4 DCB / MWh)

Table 16. General trend for potential environmental impact terrestrial ecotoxicity, relative to coal

Bioenergy scenario	Change (relative to reference case)	Main contributors to change	Further Discussion
Bioenergy scenario A		Pellet combustion Pellet plant	94% of pellet combustion ecotoxic releases from Ecoinvent emission factors. Largest contributors are zinc, phosphorus and copper emissions to air. Pellet plant ecotoxic releases are indirect from electricity consumption. Largest contributors are mercury (79%) and cadmium modeled using 2008/2009 NPRI data.
Bioenergy scenario B		Same as above	Same as above
Bioenergy scenario C		Same as above	Similar to above, but changes are less significant because co-firing with coal
Bioenergy scenario D		Same as above	Similar to above, but changes are less significant because co-firing with coal
Bioenergy scenario E		Same as above	Same as above
Bioenergy scenario F		Hog fuel combustion	Effects are less here due to no pellet production (indirect releases from electricity consumption).

Biofibre combustion is the main contributor to terrestrial ecotoxicity and this process is modelled using Ecoinvent data that was proxied with select emission factors from Envirochem's Task 5 project[71] (i.e. NOx, SO2, cadmium, lead, mercury, PAHs). The high ecotoxicity emissions are driven by emissions of zinc, phosphorus and copper emissions to air at the power plant and these emission factors come from Ecoinvent that represent European (Switzerland) conditions. It is likely that these emissions represent the metal content in European sources of wood biofibre. Biofibre combustion from Canadian-derived sources will likely emit a different profile of metals and will be dictated by the metal content found locally. At the time of this project, a complete emissions profile for Canadian derived biofibre was not available and the Envirochem work represents the current best understanding for the releases of select substances. These results should be updated if there is further chemical compositional analysis performed on Ontario-derived or Canadian-derived forest-based biomass or if empirical biofibre test burn data is available.

4.1.5 Freshwater ecotoxicity

Table 17 summarizes the change to the potential environmental impact freshwater ecotoxicity (kg 1,4 DCB / MWh)

Table 17. General trend for potential environmental impact freshwater ecotoxicity, relative to coal

Bioenergy scenario	Change (relative to reference case)	Main contributors to change	Further Discussion
Bioenergy scenario A		Coal ash disposal	Decrease in emissions as coal baseline emissions are high. Major contributors for coal and pellet combustion use Ecoinvent default data.
Bioenergy scenario B		Same as above	Same as above
Bioenergy scenario C		Same as above	Similar to above, but changes are less significant because co-firing with coal
Bioenergy scenario D		Same as above	Similar to above, but changes are less significant because co-firing with coal
Bioenergy scenario E		Same as above	Decrease in emissions as coal baseline emissions are high. Major contributors for coal and pellet combustion use Ecoinvent default data

[71] Task 5 results were obtained through personal communication (email) with Sebnem Madrali on March 7, 2012.

Bioenergy scenario F	↓	Same as above	Same as above

64% of all freshwater ecotoxic releases were from the coal ash disposal. Coal ash disposal is modelled using the Ecoinvent process of a residual material landfill (Portugal). Ecoinvent had a number of other similar landfills but all were European (i.e. Austria, Belgium, Czech Republic, Germany, Spain, France, Croatia, Italy, Netherlands, Poland and Slovakia). The landfill has a base seal with a leachate collection system and takes residual material (inorganic waste). Environmental release factors are based on data taken literature with observed leachate collection concentrations.

Of the freshwater ecotoxic releases from the landfill, the main contributors are the releases of bromine, selenium and arsenic. The type of coal ash (i.e. bituminous, sub-bituminous or lignite) was not specified by Ecoinvent; however, chemical composition was specified in the documentation and can be provided. Ontario or Canadian specific landfills were not researched or modelled.

In the pellet fuel pathway, the largest releases of freshwater ecotoxic materials came during the biomass recovery (44% of Scenario A life cycle) and pellet plant operations (29% of Scenario A life cycle).

4.1.6 Natural land transformation

Table 18 summarizes the change to the potential environmental impact natural land transformation (m^2 / MWh)

Table 18. General trend for potential environmental impact natural land transformation, relative to coal

Bioenergy scenario	Change (relative to reference case)	Main contributors to change	Further Discussion
Bioenergy scenario A	↑		
Bioenergy scenario B	↑		
Bioenergy scenario C	↑		
Bioenergy scenario D	↑		

Bioenergy scenario E	↑		
Bioenergy scenario F	↑		

<Discussion pending>

4.1.7 Fossil fuel depletion

Table 19 summarizes the change to the potential environmental impact fossil fuel depletion (kg-eq oil / MWh)

Table 19. General trend for potential environmental impact fossil fuel depletion, relative to coal

Bioenergy scenario	Change (relative to reference case)	Main contributors to change	Further Discussion
Bioenergy scenario A	↓	Biofibre fuel replacing coal	Decrease in fossil fuel depletion primarily because Ecoinvent categories coal as fossil fuel and biofibre as non-fossil fuel.
Bioenergy scenario B	↓	Biofibre fuel replacing coal	Same as above
Bioenergy scenario C	↓	Biofibre fuel replacing coal	Same as above
Bioenergy scenario D	↓	Biofibre fuel replacing coal	Same as above
Bioenergy scenario E	↓	Biofibre fuel replacing coal	Same as above
Bioenergy scenario F	↓	Biofibre fuel replacing coal	Same as above

The decrease in fossil fuel depletion is mainly due to the substitution of a fossil fuel (coal) with a renewable fuel (biofibre). In addition to fuel-switching, there are processes within both the coal and biofibre fuel pathways where fossil fuels are consumed. For example, diesel fuel is used in the coal pathway to extract coal and transport it by rail to the Atikokan generating station. Likewise, diesel fuel is used in the biofibre pathway in forestry machinery that harvests, processes and transports biofibre to the pellet plant. For Scenario A, the biofibre pathway consumes 89% less fossil fuels than the coal pathway.

4.1.8 Seral stage distribution

Table 20 summarizes the change to the potential environmental impact seral stage distribution (ha forest by seral stage).

For seral stage, a periodic increase or decrease in area of forest within a seral class does not necessarily constitute a negative environmental impact. However, the relatively permanent change to a constant age class distribution with little variation does increase risk to the maintenance of biodiversity for natural system function. Further discussion on the risk and potential biodiversity impacts for increases and decreasing seral stage classes, refer to Section 4.4.4

Table 20. General trend for potential environmental impact seral stage distribution, relative to BH0 baseline[72]

Bioenergy scenario	Seral stage	Change (relative to BH0) – mid-term (50 years)	Main contributors to change	Further Discussion
Bioenergy scenario A and bioenergy scenario C (BH2)	Early	⇧	Additional harvesting of standing trees	9% increase in early seral and 80% reduction in early-old seral. Minimal change to mid and old seral classes.
	Mid	●		
	Early-old	⇩	Additional harvesting of standing trees	
	Old	●		
Bioenergy scenario B and bioenergy scenario D (BH3)	Early	⇧	Additional harvesting of standing trees	33% increase in early seral, and decrease in all other seral stage (13% decrease for mid, 90% decrease for early-old) except old seral which does not change
	Mid	⇩	Additional harvesting of standing trees	
	Early-old	⇩	Additional harvesting of standing trees	
	Old	●		
Bioenergy scenario E and bioenergy scenario F (BH1)		●	N/A	Since there is no additional harvesting for the BH1, relative to BH0, there is no change to the seral stage

[72] The change in seral stage distribution is relative to the BH0 baseline scenario, as opposed to the coal reference case.

				distribution of the forest

<Discussion pending>

4.1.9 Fragmentation

Table 21 summarizes the change to the potential environmental impact fragmentation (km / km^2)

Table 21. General trend for potential environmental impact fragmentation, relative to BH0 baseline[73]

Bioenergy scenario	Change (relative to BH0) – mid-term (50 years)	Main contributors to change	Further Discussion
Bioenergy scenario A and bioenergy scenario C (BH2)		Additional harvesting of standing trees and requirement to build tertiary roads	24% increase in fragmentation resulting from tertiary and cutblock edges
Bioenergy scenario B and bioenergy scenario D (BH3)		Additional harvesting of standing trees and requirement to build tertiary roads.	69% increase in fragmentation
Bioenergy scenario E and bioenergy scenario F (BH1)		N/A	Since there is no additional harvesting for the BH1, relative to BH0, there is no change in fragmentation of the forest.

<Discussion pending>

4.1.10 CWD

Table 22 summarizes the change to the potential environmental impact CWD (m^3).

For CWD, a periodic increase or decrease in m3 of accumulation of decay phases of CWD does not necessarily constitute a negative environmental impact. However, the relatively permanent change to a decay phase dominated state with very little accumulation

[73] The change in CWD is relative to the BH0 baseline scenario, as opposed to the coal reference case.

debris does increase risk to the maintenance of biodiversity for natural system function. Further discussion on the risk and potential biodiversity impacts for increases and decreasing CWD, refer to Section 4.4.4

Table 22. General trend for potential environmental impact CWD, relative to BH0 baseline[74]

Bioenergy scenario	Stage	Change (relative to BH0) – mid-term (50 years)	Main contributors to change	Further Discussion
Bioenergy scenario A and bioenergy scenario C (BH2)	Accumulation	⇩	Additional harvesting of standing trees	Species or system functions dependent on accumulation phase debris will have much less opportunity in the future than they do under current conditions
	Decay	●		Little change to decay stage
Bioenergy scenario B and bioenergy scenario D (BH3)	Accumulation	⇩	Additional harvesting of standing trees	Species or system functions dependent on accumulation phase debris will have much less opportunity in the future than they do under current conditions
	Decay	⇧	Same as above	This significant and sustained increase in ground level CWD could have significant implications for nutrient cycling.
Bioenergy scenario E and bioenergy scenario F (BH1)	Accumulation	●	N/A	Since there is no additional harvesting for the BH1 relative to BH0, there is no change to CWD in the forest. The definition of CWD in this work does not include roadside slash and therefore the change in roadside slash due to collection in BH1 does also not impact CWD.
	Decay			

<Discussion pending>

[74] The change in CWD is relative to the BH0 baseline scenario, as opposed to the coal reference case.

4.2 Bioenergy scenarios – Details

Sections 4.2.1 to 4.2.6 provide further quantification results on the changes in the potential environmental impacts from coal, organized by each bioenergy scenario. These sections include the graphs that show the difference and percentage difference between the bioenergy scenarios and coal. Actual data is included in tables in Appendix D.

Notes:

1. **Forest carbon and inclusion in the climate change impact –** As mentioned in Section 4.1.1, the 100-year average GHG emissions (tonnes CO2e / MWh) from the forest carbon component has been combined with the LCA. The GHG emissions results in Section 4.2.1 to Section 4.2.6 only summarize the GHG emissions for each bioenergy scenario. For a more detailed discussion on the quantification of the GHG emissions related to forest carbon, refer to Section 4.3.
2. **Landscape-level environmental impacts** – Because of the obscurity of non-conventional environmental impacts as they relate to traditional life cycle methods, the three landscape-level environmental impacts have not been normalized to the LCA functional unit in the sections below and have not been included in the tables. A brief summary is provided for these landscape-level indicators and Section 4.4 provides details on these landscape-level indicators.

4.2.1 Bioenergy scenario A

Figure 14 and Table 23 summarizes the difference in potential environmental impacts when transitioning from 100% coal combustion to 100% white pellets sourced from hardwood biofibre chips to produce electricity. Figure 15 and Table 24 summarizes the percentage (%) change from coal to bioenergy scenario A and the following figures show these changes graphically.

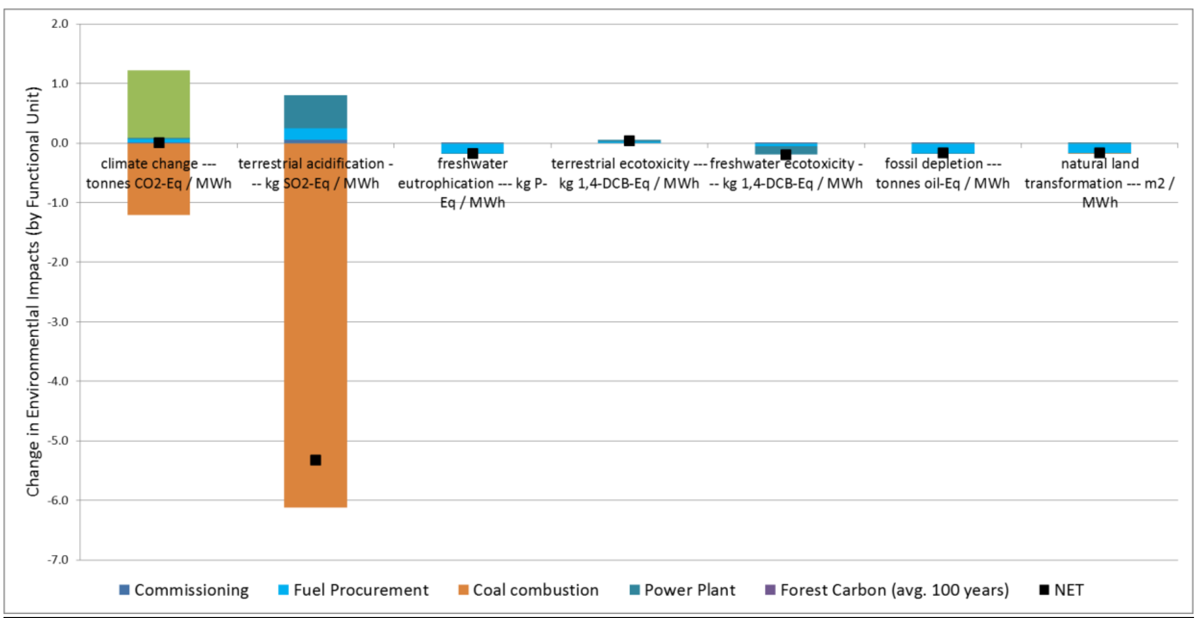


Figure 14. Change in potential environmental impacts – Coal reference case to bioenergy scenario A

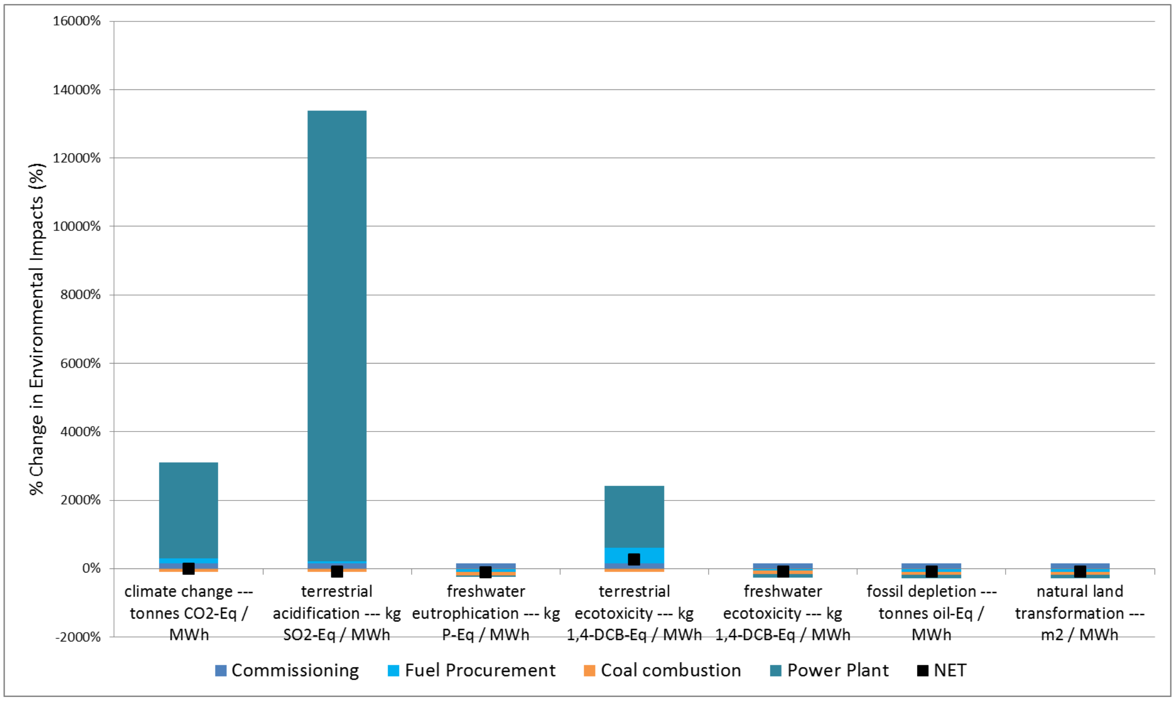


Figure 15. % change in potential environmental impacts – Coal reference case to bioenergy scenario A

Table 23. Change in potential environmental impacts – Coal reference case to bioenergy scenario A

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	0.0106	0.0488	0.0013	0.0018	0.0044	0.0034	0.0049
	Fuel Procurement	0.0566	0.1965	-0.1745	0.0201	-0.0483	-0.1659	-0.1713
	Coal combustion	-1.2101	-6.1247	-0.0001	-0.0080	-0.0031	-0.0009	-0.0008
	Power Plant	0.0211	0.5597	0.0000	0.0278	-0.1455	-0.0006	0.0044
	LCA Total	**-1.1218**	**-5.3196**	**-0.1733**	**0.0418**	**-0.1925**	**-0.1640**	**-0.1628**
	Forest Carbon (avg. 100 years)	**1.1326**						
	NET	**0.0108**	**-5.3196**	**-0.1733**	**0.0418**	**-0.1925**	**-0.1640**	**-0.1628**

Table 24. % change in potential environmental impacts – Coal reference case to bioenergy scenario A

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	148%	156%	148%	159%	161%	154%	154%
	Fuel Procurement	160%	67%	-99%	458.24%	-59%	-89%	-89%
	Coal combustion	-100%	-100%	-100%	-100%	-100%	-100%	-100%
	Power Plant	2794%	13172%	-43%	1804%	-94%	-97%	-98%
	LCA Total	-89%	-82%	-97%	277%	-79%	-86%	-84%
	Forest Carbon (avg. 100 years)							
	NET	**0.9%**	**-82%**	**-97%**	**277%**	**-79%**	**-86%**	**-84%**

4.2.2 Bioenergy scenario B

Figure 16 and Table 25 summarizes the difference in potential environmental impacts when transitioning from 100% coal combustion to 100% white pellets sourced from hardwood logs to produce electricity. Figure 17 and Table 26 summarizes the percentage (%) change from coal to bioenergy scenario B and the following figures show these changes graphically.

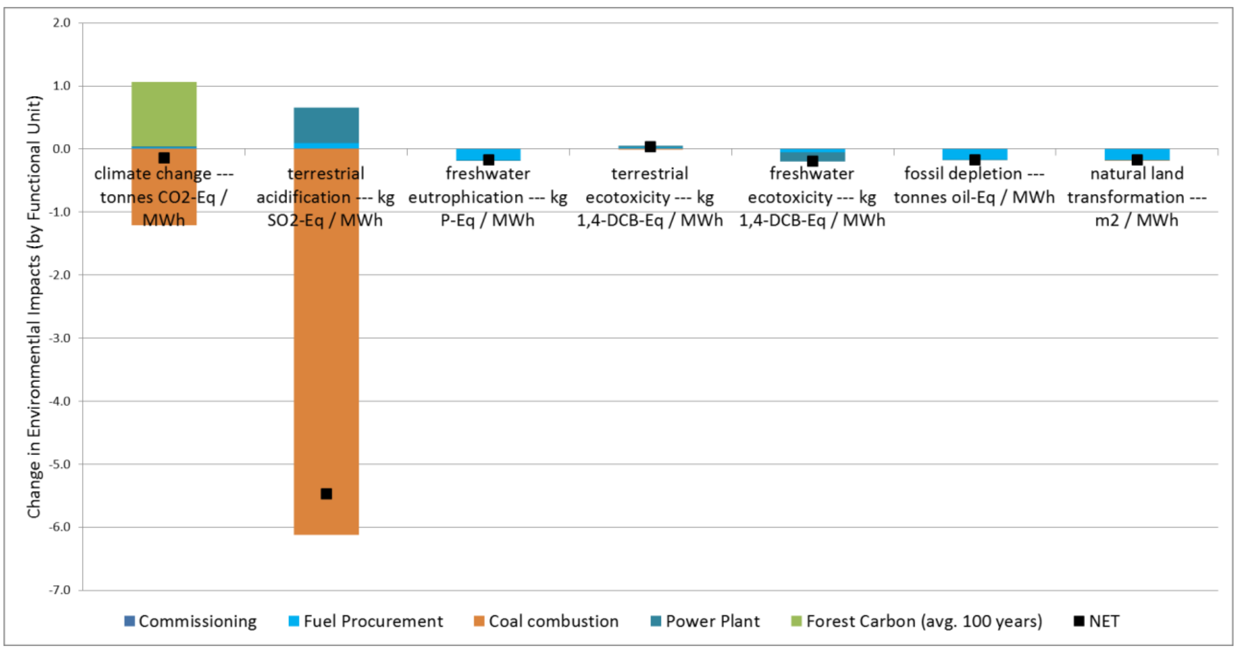


Figure 16. Change in potential environmental impacts – Coal reference case to bioenergy scenario B

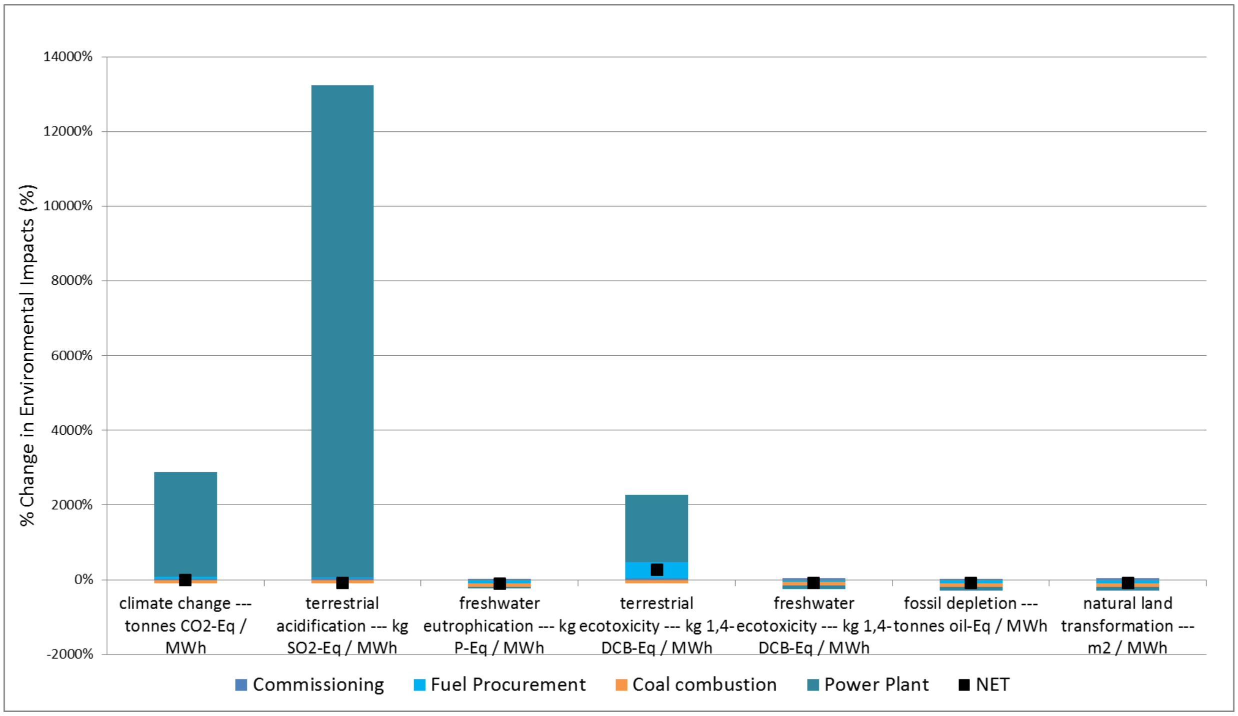


Figure 17. % change in potential environmental impacts – Coal reference case to bioenergy scenario B

Table 25. Change in potential environmental impacts – Coal reference case to bioenergy scenario B

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	0.0018	0.0106	0.0002	0.0004	0.0010	0.0007	0.0010
	Fuel Procurement	0.0194	0.0873	-0.1746	0.0187	-0.0488	-0.1718	-0.1790
	Coal combustion	-1.2101	-6.1247	-0.0001	-0.0080	-0.0031	-0.0009	-0.0008
	Power Plant	0.0211	0.5597	0.0000	0.0278	-0.1455	-0.0006	0.0044
	LCA Total	**-1.1678**	**-5.4670**	**-0.1745**	**0.0390**	**-0.1962**	**-0.1725**	**-0.1744**
	Forest Carbon (avg. 100 years)	**1.0245**						
	NET	**-0.1433**	**-5.4670**	**-0.1745**	**0.0390**	**-0.1962**	**-0.1725**	**-0.1744**

Table 26. % change in potential environmental impacts – Coal reference case to bioenergy scenario B

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	25%	34%	26%	36%	38%	31%	32%
	Fuel Procurement	55%	30%	-99%	427%	-59%	-92%	-93%
	Coal combustion	-100%	-100%	-100%	-100%	-100%	-100%	-100%
	Power Plant	2794%	13172%	-43%	1804%	-94%	-97%	-98%
	LCA Total	-93%	-85%	-98%	258%	-81%	-91%	-90%
	Forest Carbon (avg. 100 years)							
	NET	**-11%**	**-85%**	**-98%**	**258%**	**-81%**	**-91%**	**-90%**

4.2.3 Bioenergy scenario C

Figure 18 and Table 27 summarizes the difference in potential environmental impacts when transitioning from 100% coal combustion to 65% white pellets sourced from hardwood biofibre chips / 35% coal (on an energy basis) to produce electricity. Figure 19 and

Table 28 summarizes the percentage (%) change from coal to bioenergy scenario C and the following figures show these changes graphically.

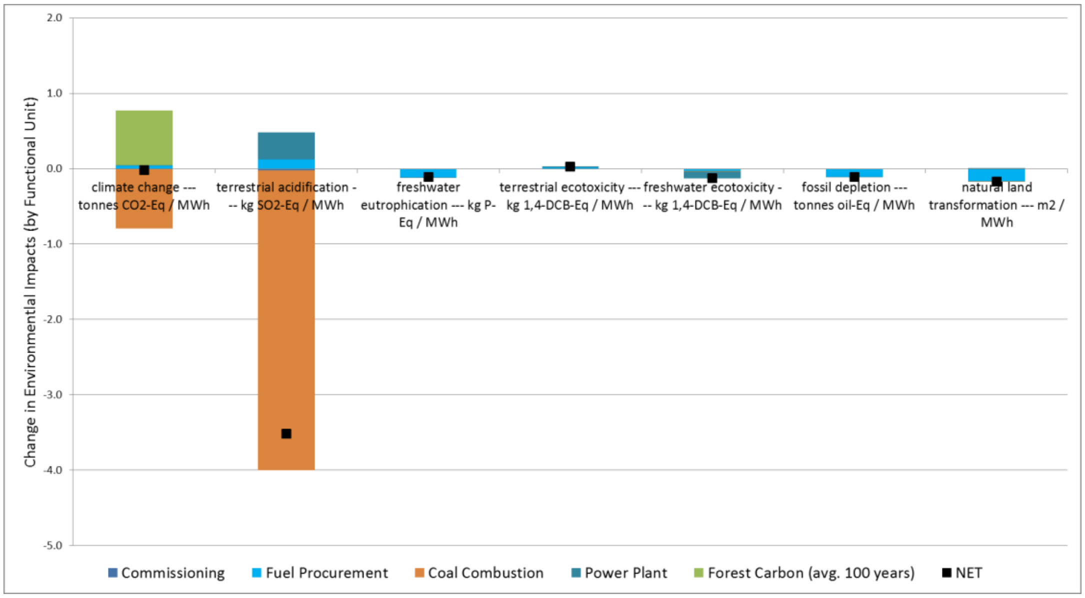


Figure 18. Change in potential environmental impacts – Coal reference case to bioenergy scenario C

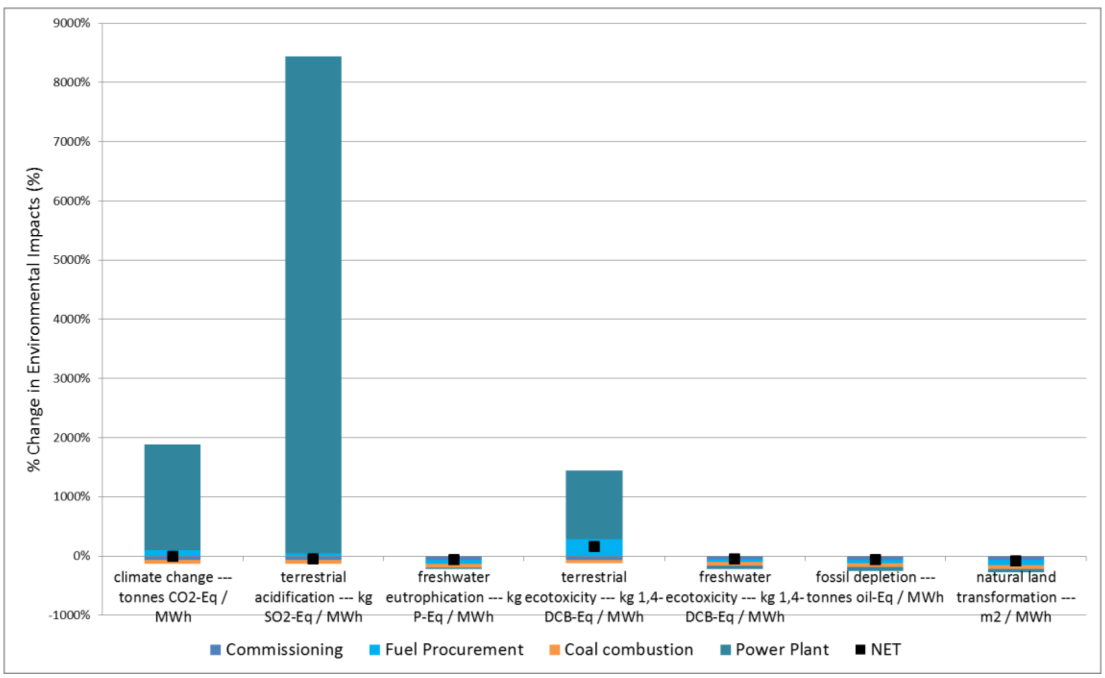


Figure 19. % change in potential environmental impacts – Coal reference case to bioenergy scenario C

Table 27. Change in potential environmental impacts – Coal reference case to bioenergy scenario C

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	-0.0049	-0.0195	-0.0006	-0.0007	-0.0016	-0.0014	-0.0021
	Fuel Procurement	0.0361	0.1250	-0.1115	0.0128	-0.0309	-0.1061	-0.1689
	Coal Combustion	-0.7866	-3.9810	-0.0001	-0.0052	-0.0020	-0.0006	-0.0005
	Power Plant	0.0134	0.3570	0.0000	0.0177	-0.0930	-0.0004	0.0028
	LCA Total	**-0.7420**	**-3.5186**	**-0.1122**	**0.0246**	**-0.1275**	**-0.1084**	**-0.1687**
	Forest Carbon (avg. 100 years)	**0.7224**						
	NET	**-0.0196**	**-3.5186**	**-0.1122**	**0.0246**	**-0.1275**	**-0.1084**	**-0.1687**

Table 28. % change in potential environmental impacts – Coal reference case to bioenergy scenario C

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	-68%	-63%	-68%	-61%	-60%	-64%	-64%
	Fuel Procurement	102%	42%	-63%	292%	-37%	-57%	-87%
	Coal combustion	-65%	-65%	-65%	-65%	-65%	-65%	-65%
	Power Plant	1782%	8401%	-28%	1151%	-60%	-62%	-62%
	LCA Total	-59%	-55%	-63%	163%	-53%	-57%	-88%
	Forest Carbon (avg. 100 years)							
	NET	**-2%**	**-55%**	**-63%**	**163%**	**-53%**	**-57%**	**-88%**

4.2.4 Bioenergy scenario D

Figure 20 and Table 29 summarizes the difference in potential environmental impacts when transitioning from 100% coal combustion to 65% white pellets sourced from hardwood logs / 35% coal (on an energy basis) to produce electricity. Figure 21 and Table 30 summarizes the percentage (%) change from coal to bioenergy scenario D and the following figures show these changes graphically.

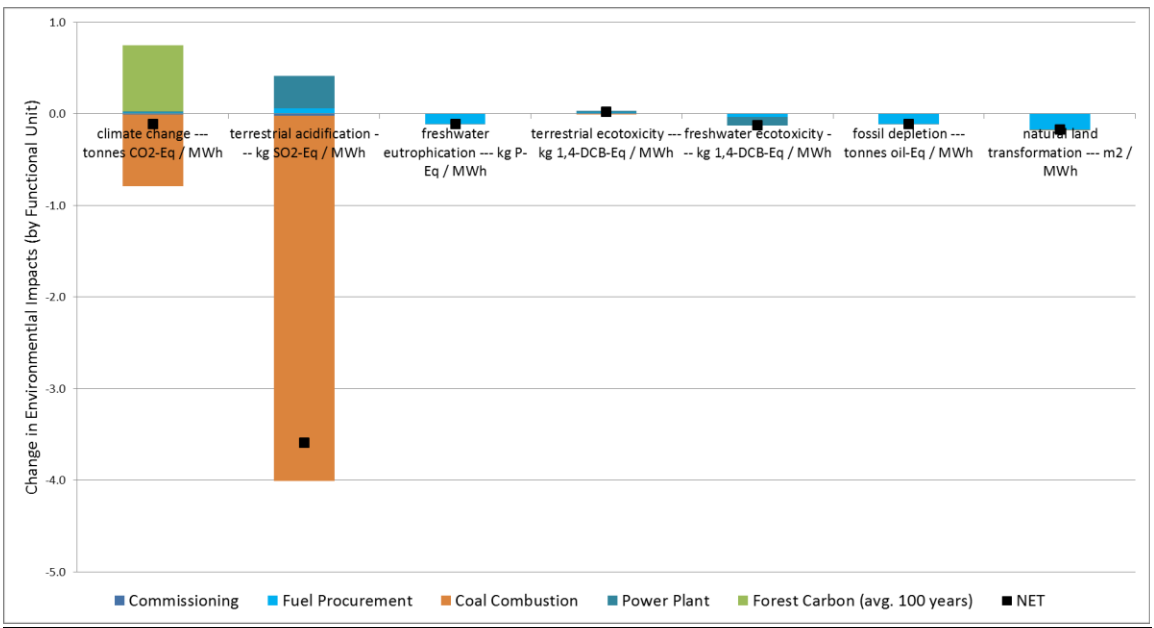


Figure 20. Change in potential environmental impacts – Coal reference case to bioenergy scenario D

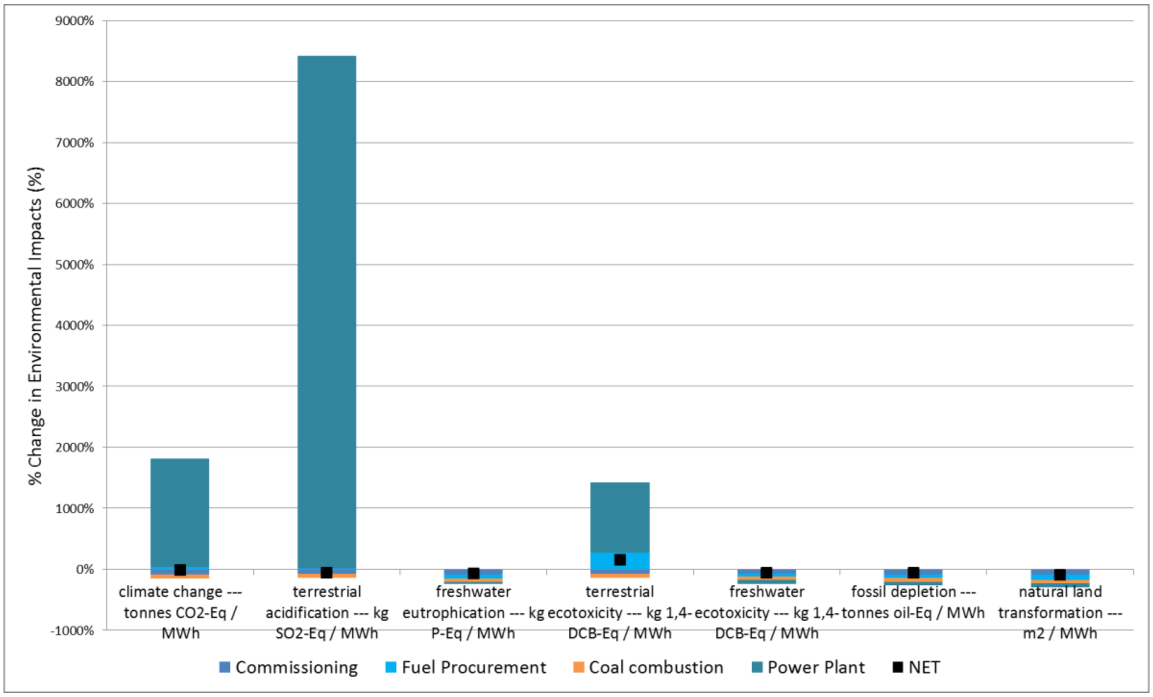


Figure 21. % change in potential environmental impacts – Coal reference case to bioenergy scenario D

Table 29. Change in potential environmental impacts – Coal reference case to bioenergy scenario D

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	-0.0060	-0.0244	-0.0007	-0.0009	-0.0020	-0.0018	-0.0026
	Fuel Procurement	0.0123	0.0553	-0.1116	0.0120	-0.0312	-0.1098	-0.1738
	Coal Combustion	-0.7866	-3.9810	-0.0001	-0.0052	-0.0020	-0.0006	-0.0005
	Power Plant	0.0134	0.3570	0.0000	0.0177	-0.0930	-0.0004	0.0028
	LCA Total	**-0.7668**	**-3.5931**	**-0.1124**	**0.0236**	**-0.1282**	**-0.1125**	**-0.1741**
	Forest Carbon (avg. 100 years)	**0.6534**						
	NET	**-0.1134**	**-3.5931**	**-0.1124**	**0.0236**	**-0.1282**	**-0.1125**	**-0.1741**

Table 30. % change in potential environmental impacts – Coal reference case to bioenergy scenario D

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	-84%	-78%	-84%	-77%	-75%	-80%	-80%
	Fuel Procurement	35%	19%	-63%	272%	-38%	-59%	-90%
	Coal combustion	-65%	-65%	-65%	-65%	-65%	-65%	-65%
	Power Plant	1782%	8401%	-28%	1151%	-60%	-62%	-62%
	LCA Total	-61%	-56%	-63%	156%	-53%	-59%	-90%
	Forest Carbon (avg. 100 years)							
	NET	**-9%**	**-56%**	**-63%**	**156%**	**-53%**	**-59%**	**-90%**

4.2.5 Bioenergy scenario E

Figure 22 and Table 31 summarizes the difference in potential environmental impacts when transitioning from 100% coal combustion to 100% brown pellets sourced from roadside slash to produce electricity. Figure 23 and Table 32 summarizes the percentage (%) change from coal to bioenergy scenario E and the following figures show these changes graphically.

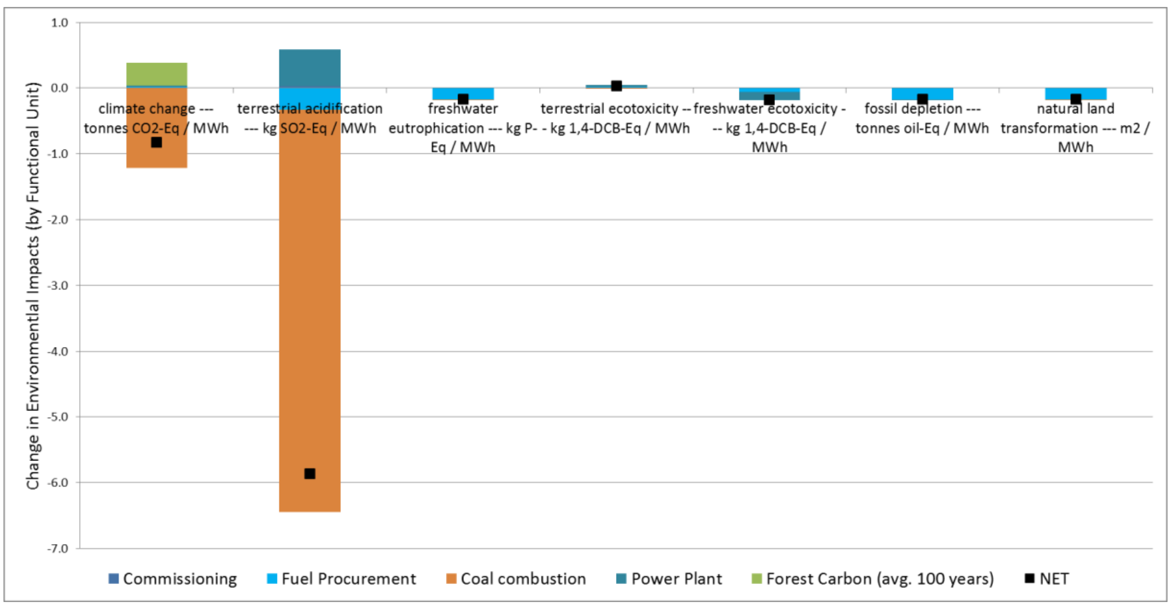


Figure 22. Change in potential environmental impacts – Coal reference case to bioenergy scenario E

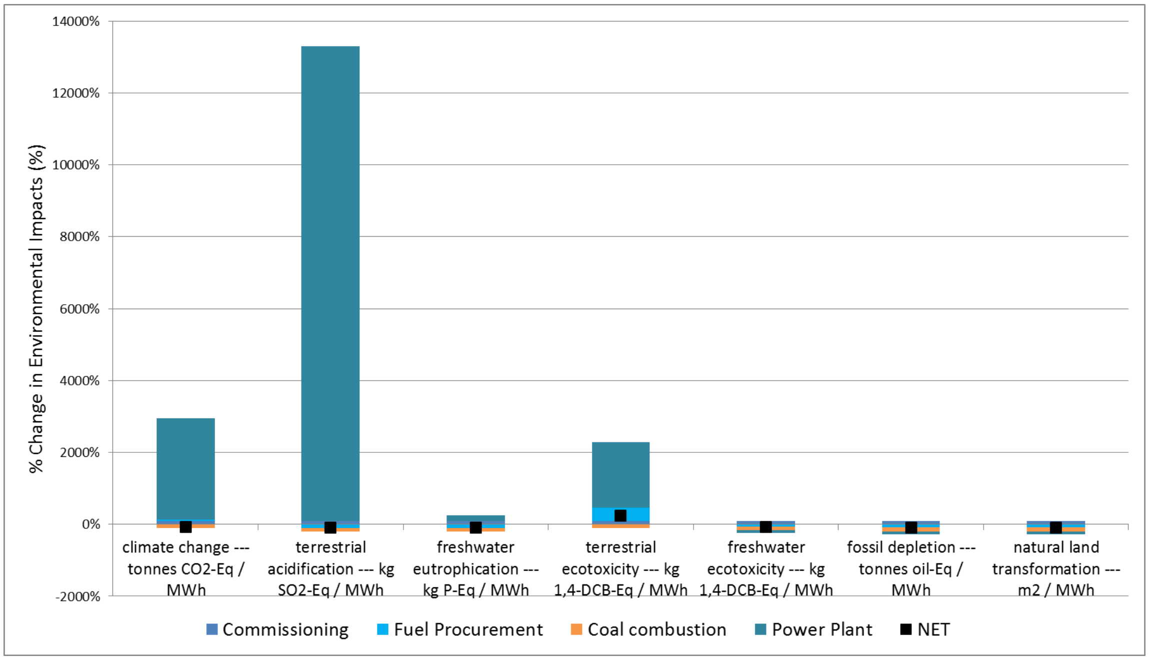


Figure 23. % change in potential environmental impacts – Coal reference case to bioenergy scenario E

Table 31. Change in potential environmental impacts from coal reference case to bioenergy scenario E

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	0.0065	0.0283	0.0008	0.0011	0.0025	0.0020	0.0030
	Fuel Procurement	0.0121	-0.3238	-0.1747	0.0168	-0.0550	-0.1705	-0.1777
	Coal combustion	-1.2101	-6.1247	-0.0001	-0.0080	-0.0031	-0.0009	-0.0008
	Power Plant	0.0212	0.5609	0.0001	0.0278	-0.1225	-0.0005	0.0040
	LCA Total	**-1.1703**	**-5.8591**	**-0.1739**	**0.0376**	**-0.1780**	**-0.1698**	**-0.1714**
	Forest Carbon (avg. 100 years)	**0.3435**						
	NET	**-0.8268**	**-5.8591**	**-0.1739**	**0.0376**	**-0.1780**	**-0.1698**	**-0.1714**

Table 32. % change in potential environmental impacts from coal reference case to bioenergy scenario E

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	90%	91%	89%	90%	94%	90%	95%
	Fuel Procurement	34%	-110%	-99%	382%	-67%	-92%	-92%
	Coal combustion	-100%	-100%	-100%	-100%	-100%	-100%	-100%
	Power Plant	2816%	13200%	169%	1805%	-79%	-86%	-89%
LCA Total		-93%	-91%	-98%	249%	-73%	-90%	-89%
0	Forest Carbon (avg. 100 years)							
0	**NET**	**-66%**	**-91%**	**-98%**	**249%**	**-73%**	**-90%**	**-89%**

4.2.6 Bioenergy scenario F

Figure 24 and Table 33 summarizes the difference in potential environmental impacts when transitioning from 100% coal combustion to 100% hog fuel sourced[75] from roadside slash to produce electricity. Figure 25 and Table 34 summarizes the percentage (%) change from coal to bioenergy scenario F and the following figures show these changes graphically.

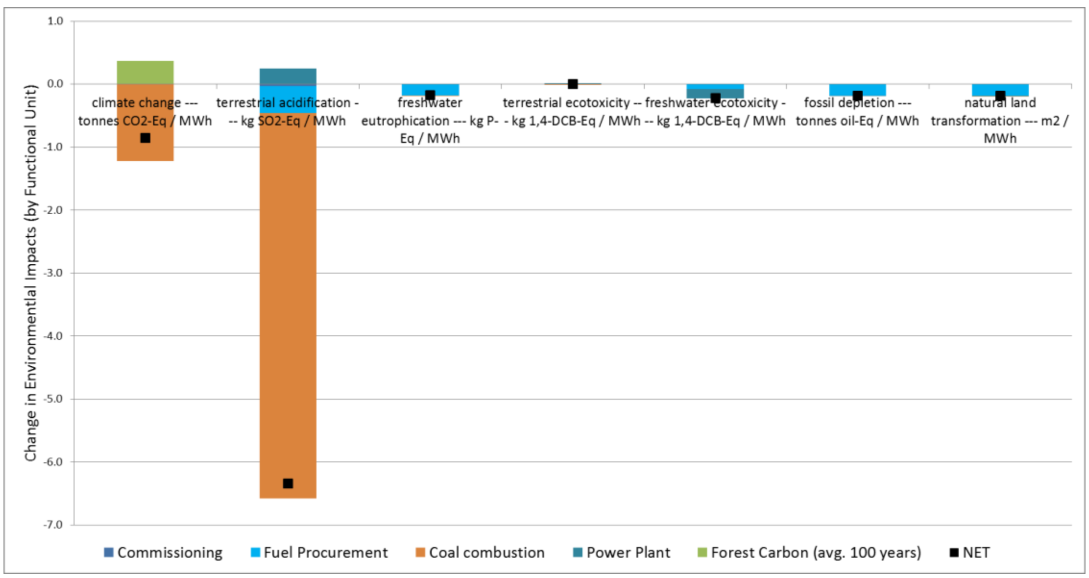


Figure 24. Change in potential environmental impacts – Coal reference case to bioenergy scenario F

[75] The "modified cogen" results are show here.

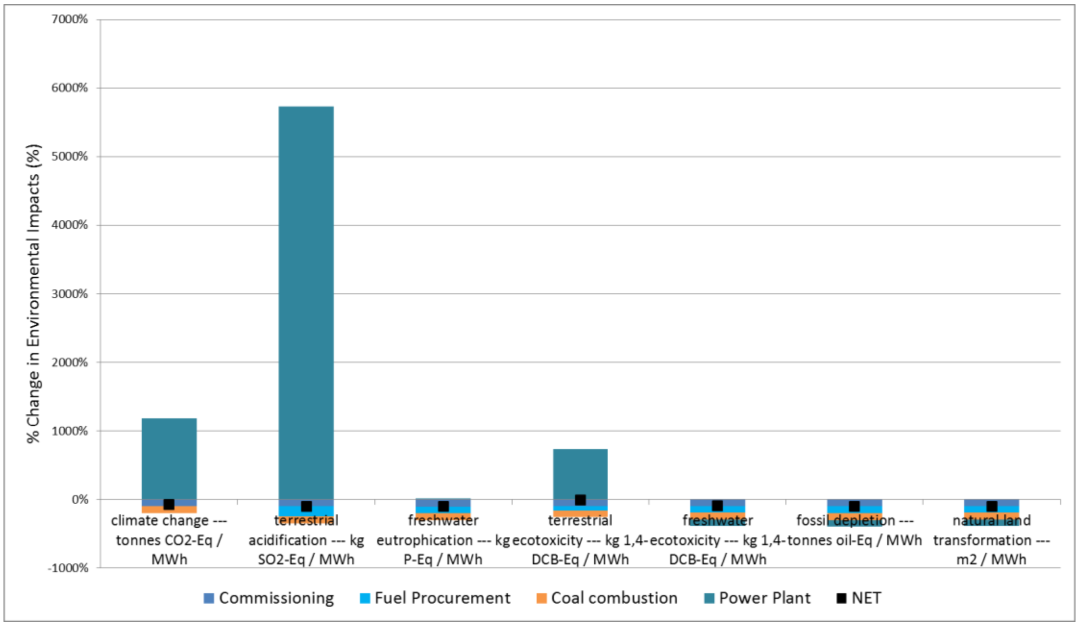


Figure 25. % change in potential environmental impacts – Coal reference case to bioenergy scenario F

Table 33. Change in potential environmental impacts – Coal reference case to bioenergy scenario F

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	-0.0071	-0.0306	-0.0009	-0.0011	-0.0027	-0.0022	-0.0030
	Fuel Procurement	0.0017	-0.4264	-0.1768	-0.0026	-0.0757	-0.1807	-0.1873
	Coal combustion	-1.2101	-6.1247	-0.0001	-0.0080	-0.0031	-0.0009	-0.0008
	Power Plant	0.0089	0.2436	0.0000	0.0113	-0.1403	-0.0005	0.0043
	LCA Total	**-1.2066**	**-6.3381**	**-0.1777**	**-0.0004**	**-0.2217**	**-0.1844**	**-0.1868**
	Forest Carbon (avg. 100 years)	**0.3557**						
	NET	**-0.8509**	**-6.3381**	**-0.1777**	**-0.0004**	**-0.2217**	**-0.1844**	**-0.1868**

Table 34. % change in potential environmental impacts – Coal reference case to bioenergy scenario F

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	-99%	-98%	-100%	-99%	-98%	-99%	-93%
	Fuel Procurement	5%	-144%	-100%	-60%	-92%	-97%	-97%
	Coal combustion	-100%	-100%	-100%	-100%	-100%	-100%	-100%
	Power Plant	1179%	5733%	18%	736%	-91%	-94%	-95%
	LCA Total	-96%	-98%	-100%	-3%	-91%	-97%	-97%
	Forest Carbon (avg. 100 years)							
	NET	**-68%**	**-98%**	**-100%**	**-3%**	**-91%**	**-97%**	**-97%**

4.3 GHG emissions

The total GHG emissions for each bioenergy scenario are calculated by adding the LCA *climate change* (tonnes CO_2e / MWh) results and the GHG emissions from the forest carbon results. The LCA climate change results included all upstream emissions from harvesting, comminution, silviculture, transportation, pelletization and power plant activities. The biogenic CO_2 emissions from combusting the slash used for process drying at the pellet plant and the biogenic CO_2 emissions from combusting the pellets or hog fuel at the power plant are not included in the LCA climate change results and are accounted for in the forest carbon results. Combining these two sources of GHG emissions provides an overall GHG emission profile for the bioenergy scenarios that takes into consideration the biogenic carbon emissions from biofibre combustion balanced by the uptake of carbon by the forest.

4.3.1 Forest carbon for biofibre harvest scenarios

The change in forest carbon as a result of annual biofibre harvesting was calculated for each biofibre harvest scenarios (BH1, BH2 and BH3), relative to their respective BH0 baseline harvest scenario[76].

The forest carbon modelling, as presented in Section 2.3, utilized the FORCARB-ON modelling platform to perform the analysis. The start date for the modelling was 2015 and the total forest pools for this analysis included the six forest carbon pools, carbon in roadside slash and carbon in black carbon. The details of these forest carbon pools are also discussed in Section 2.3.

Change in forest carbon extracting and combusting biofibre

The forest carbon modelling in this work quantifies the change in carbon as a result of combusting the biofibre slash used in the drying process (BH1 and BH2), bark used in the drying

[76] For the forest carbon modelling, there is a BH0 baseline scenario for each of the BH1, BH2 and BH3 bioharvest scenarios. Specifically, for BH2 and BH3, this is because the change in forest carbon needs to be compared to the landbase where the trees harvested in BH2 and BH3 would *not* be harvested. The forest carbon modelling incorporates these respective BH0 baseline scenarios in the results but does not explicitly provide results for the BH0 baselines.

process (BH3), brown pellets (BH1) and white pellets (BH2 and BH3). The amount of carbon contained[77] in the annual biofibre requirements (ODT/year) are essentially *removed* from the overall forest carbon pool each year. This forest carbon modelling quantifies the impact of removing this amount of annual biofibre on the overall forest and also quantifies and the change in carbon resulting from the BH0 roadside burning of the slash.

Table 35 summarizes the change in forest carbon (for each 10-year time period) from 2015–2115 and Figure 26 summarizes the total forest carbon for each biofibre harvest scenario compared to the baseline (BH0). A positive change in forest carbon indicates that the biofibre harvest scenario results in a *sink* of carbon emissions (the forest has gained more carbon than lost carbon during the time period and has sequestered carbon) and a negative change in forest carbon indicates that the biofibre harvest scenario results in a *source* of carbon emissions (the forest has lost more carbon than gained carbon during the time period and has released carbon).

[77] An assumption of 0.5 tonnes C / ODT biofibre was used in the forest carbon modelling.

Table 35. 10-year change in forest carbon for each biofibre harvest scenario, relative to BH0

	Change in total forest carbon (Millions tonnes carbon / 10-year)										
	2015	**2025**	**2035**	**2045**	**2055**	**2065**	**2075**	**2085**	**2095**	**2105**	**2115**
BH1 - Scenario E	0	-1.33	-1.07	-0.87	-0.71	-0.59	-0.49	-0.40	-0.34	-0.28	-0.24
BH1 - Scenario F	0	-0.04	-0.03	-0.03	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01
BH2	0	-4.69	-4.38	-3.44	-2.27	-1.24	-0.51	-0.09	0.15	0.26	0.28
BH3	0	-9.11	-8.45	-6.50	-4.12	-2.03	-0.60	0.19	0.60	0.77	0.77

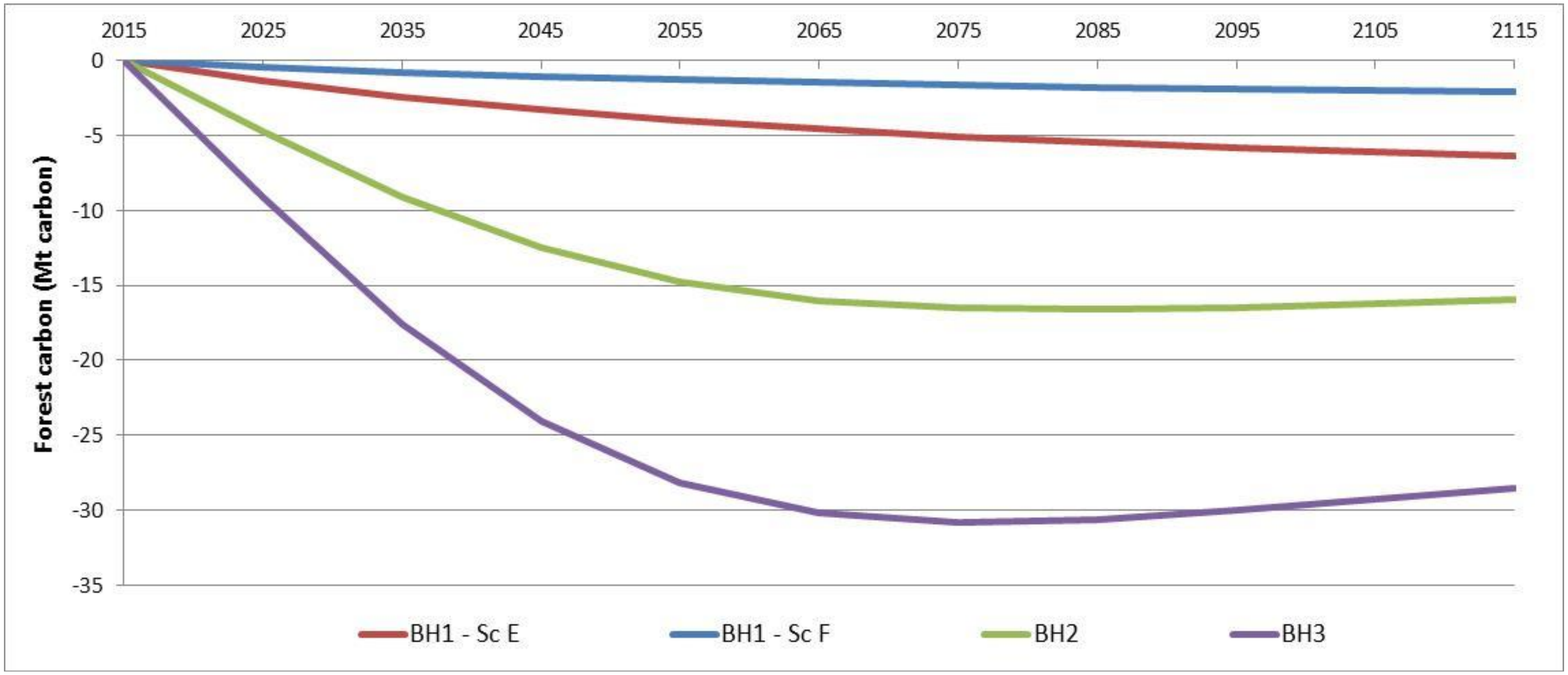


Figure 26. Change in total forest carbon for each biofibre harvest scenario, relative to BH0

Generally, Figure 26 shows that all biofibre harvest scenarios result in a net decrease of carbon in the landbase throughout the planning horizon based on the defined continuous harvest levels of biofibre for wood pellets and hog fuel.

Biofibre harvest scenario BH1 shows the smallest decrease in carbon. Bioharvest scenario BH2 shows a further carbon decrease than bioharvest scenario BH1 and BH3 shows an even further carbon decrease than BH2. It is important to note that the net decrease of carbon in the landbase is not strictly the carbon lost from the annual biofibre harvesting volume for each bioharvest scenario – there is a further decrease as a result of the changes introduced from harvesting – both in tree growth if the trees were not harvested and continued to grow, and the amount of additional slash that is generated from harvesting the trees. This additional slash is both included in the downed wood debris carbon pool in the forest and the additional roadside slash and both carbon pools will decompose over time.

However, for biofibre harvest scenarios BH2 and BH3, there is an increase in carbon sequestration in the forest, but this does not happen until 2085 (BH2) and 2095 (BH3). These different inflection points are a result of the different harvested forest units, the stand age at the time of harvest, and the post-harvest growth curves compared to the pre-harvest growth curves.

4.3.1.1 Biofibre harvest Scenario 1 (BH1) - Slash

Scenario E and Scenario F

These scenarios represent the smallest change in forest carbon, compared to the other biofibre harvest scenarios. This smaller change can be attributed to the fact that there is no increase in tree harvesting and the source of the biofibre utilized is 100% of the roadside slash. Under the BHO baseline, approximately 33% of the roadside slash is burned. During this roadside slash burning, a very small percentage (2.25%) of the carbon in the burned slash is converted to black carbon, and the remaining carbon is modelled to naturally decompose.

It is observed that the change in forest carbon in both these two scenarios, although it does approach steady state, it does not reach this steady state in the timeframe of the analysis. This is likely due to the decomposition rate modelled for the roadside slash. A quick model re-run was performed to extend the 100-year planning horizon and steady state does occur after the 100-year planning horizon.

4.3.1.2 Biofibre harvest Scenario 2 (BH2) – Increased hardwood harvesting

Scenario A and Scenario C

The BH2 scenario as seen in Figure 26 shows a larger decrease in forest carbon where the overall scenario is a carbon source up until the year 2095 at which point the landbase becomes a carbon sink and carbon is being sequestered at a faster rate than being removed. The carbon loss rate is largest at the beginning of the planning horizon and slowly decreases over time as the landbase is able to resequester carbon. The higher carbon loss in BH2, compared to BH1, is attributed to the fact that there is an increase in hardwood tree harvesting to provide the biofibre for the white pellets. In the respective BAU scenario for BH2, these trees are left unharvested and would continue to grow and decay defined by their growth and yield curves.

The BH2 scenario utilizes a smaller annual amount of white pellets (296,896 ODT / year) compared to the BH1 scenario (377,345 ODT / year) but results in a higher source of carbon emissions. This again is attributed to the fact the BH2 is harvesting standing trees instead of utilizing slash — activities which have very different carbon implications.

4.3.1.3 Biofibre harvest Scenario 3 (BH3) – further increased hardwood harvesting

Scenario B and Scenario D

The BH3 scenario as seen in Figure 26 shows yet a further decrease in forest carbon where the overall scenario is a carbon source up until the year 2085 at which point the landbase becomes a carbon sink and carbon is being sequestered at a faster rate than being removed. Similar to BH2, the carbon loss rate is largest at the beginning of the planning horizon and slowly decreases over time as the landbase is able to resequester carbon. Similar to BH2, the higher carbon loss in BH3, compared to BH1, is attributed to the fact that there is a further increase in hardwood tree harvesting to provide the biofibre for the white pellets. In the respective BAU scenario for BH3, these trees are left unharvested and would continue to grow and decay defined by their growth and yield curves.

4.3.2 Comparison to previous forest carbon studies

A study completed in 2010 examined the impacts of harvesting both in-forest slash and trees from the upper Great Lakes St. Lawrence forest region for the production and co-firing of wood pellets and the use of ethanol over a 100-year planning horizon. [78] McKechnie et. al. examined the combined GHG emissions from both the upstream LCA GHG emissions and the change in forest carbon as a result of harvesting these two sources.

Table 36 summarizes the scope of the forest carbon modelling for that study as compared to this work.

Table 36. Parameters for the McKechnie and the EC biomass studies

	McKechnie et. al.	EC LCA biomass project
Landbase	GLSL forest region, 10 FMUs	Predominately Boreal forest region, 4 FMUs
Landbase Area	5.25 M ha	~ 2.6 M ha
Amount of forest slash (residue) used in forest carbon modelling	0.38M ODT / year (in-forest slash)	0.442M ODT / year (roadside slash)
BAU handling of slash	Slash remains in-forest and left to decompose	Approximately 33% is burned at roadside. 85% of carbon in burned slash is converted to CO2.

[78] McKechnie et. al., "Forest Bioenergy or Forest Carbon? Assessing the Trade-offs in Greenhouse Gas Mitigation with wood-based Fuels," *Environmental Science and Technology*, 45 (2) 2011: 789 - 795

		Remaining carbon in slash piles decays at a slower decay rate than in-forest residue
Standing trees – Amount of trees harvested in forest carbon modelling	1.8M ODT / year	BH2 – 0.297M ODT / year BH3 – 0.587M ODT / year
BAU – Standing trees	Trees are not harvested	Trees are not harvested
Forest Carbon Modelling Platform	FORCARB-ON	FORCARB-ON

In summary, McKechnie et. al. found that there was a decrease in forest carbon resulting from the extraction of biofibre from both slash and standing trees used to make pellets for electricity combustion.

Figure 27 provides a comparison of carbon loss, converted to GHG emissions, between the slash scenario in McKechnie et. al. and the BH1 scenario.

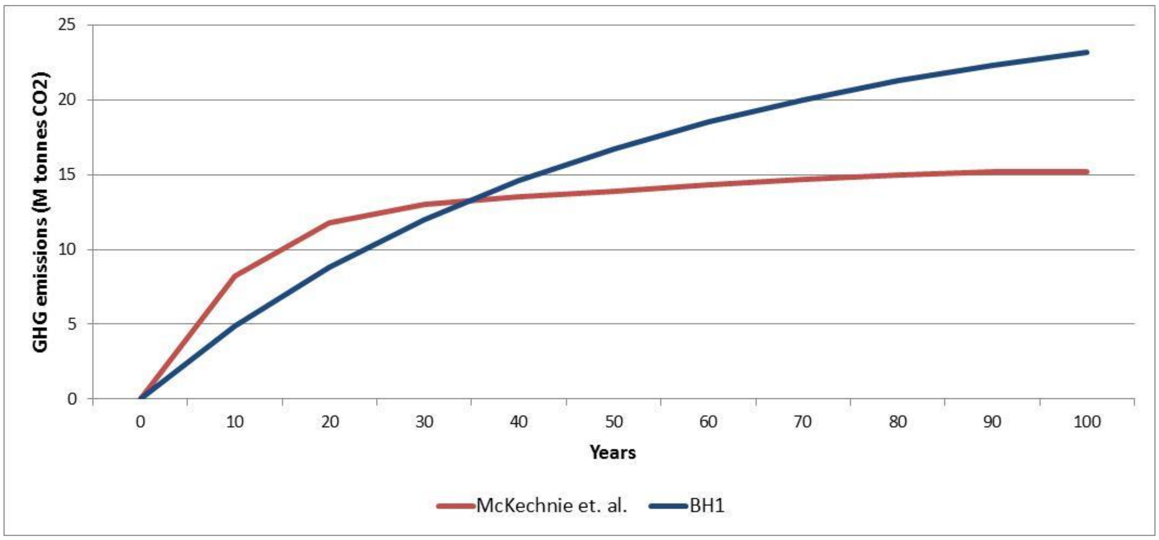


Figure 27. Comparative GHG emissions between McKechnie et. al. (in-forest slash) and BH1 (roadside slash)

Both studies show similar GHG emissions profiles for a very similar annual amount of biofibre slash used. The BH1 scenario results (which is relative to the BH0 baseline) has few GHG emissions at the start of the planning horizon compared to the McKechnie et. al. analysis. This is because in the BH0 scenario a percentage of roadside slash is modelled as being burned, which offers a GHG advantage to the BH1 scenario. However, in the McKechnie et. al. analysis, the GHG emission profile reaches steady state (around 80 years), while the BH1 scenario does not reach steady state within the planning horizon. It is hypothesized that this difference is due to the faster decay rates applied to the in-forest slash compared to the decay rates of the roadside slash. Another possible contributing factor is that the McKechnie et. al. analysis models the GLSL forest region which has a higher percentage of hardwood species than the Boreal forest region, which is predominately softwood species. Hardwood species tend to decompose at a faster rate than softwood species.

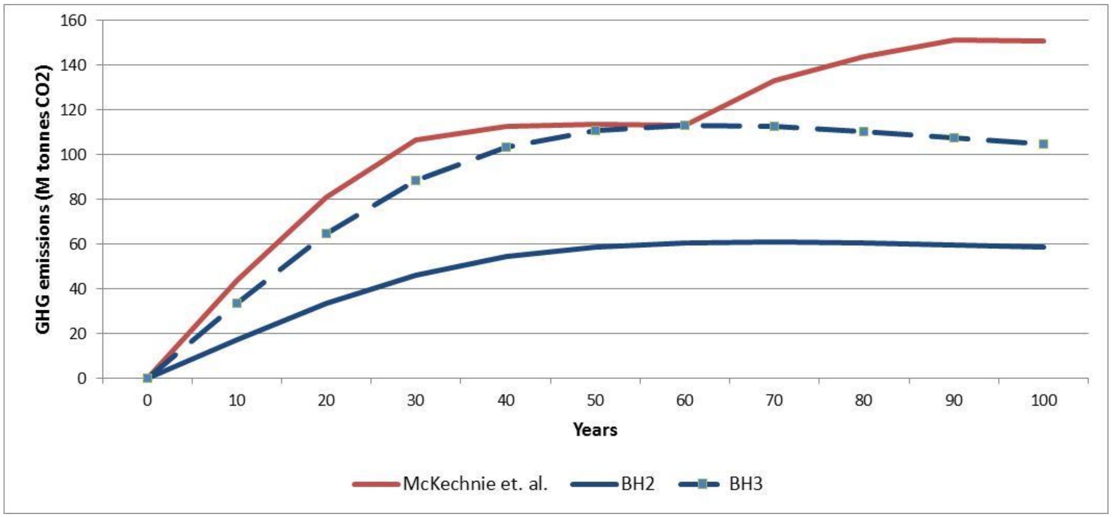


Figure 28. Comparative GHG emissions between McKechnie et. al. (tree harvesting), BH2 and BH3 (tree harvesting)

Comparing tree harvesting, both studies also have similar GHG emissions profiles, although the amount of biofibre used is quite different. The amount of biofibre used in BH2 is approximately 20% higher than the McKechnie et. al. analysis and the amount of biofibre used in BH3 is approximately 38% higher than the McKechnie et. al. analysis. The corresponding magnitude of GHG emission profiles in turn do not match these percentages and the BH2 and BH3 profiles have GHG emissions / ODT biofibre much higher than McKechnie.

Comparisons between the two studies are extremely difficult as the forest carbon modelling is affected by:

- Different age structures at the beginning of the harvest, and different starting timeframes
- Succession rules
- Disturbance regimes
- Biofibre harvest methods

The following is a list of potential reasons the BH2 and BH3 GHG emissions are different than the McKechnie et. al. results:[79]

- The BH2 and BH3 harvesting occurs in the Boreal forest region where tree growth is much slower than the GLSL forest region
- Different starting age structures of the forests
- Successional changes in the GLSL forest take place earlier than in the Boreal forest region

[79] This list was generated with the help of OMNR and the forest carbon modelling team

- The harvesting method utilized in the Boreal forest region is predominately clearcut whereas in the GLSL forest region, the prevalent harvest method is selection cut. Selection harvesting does not deplete forest carbon stocks as much as in clearcut operations.

4.3.3 LCA GHG emissions (Climate Change – CO_2e / MWh)

The life cycle GHG emissions for all activities related to the harvesting, processing, comminution, transportation, pelletization and combustion have been quantified through the LCA portion of this work. This analysis quantified the Climate Change environmental impact category on a per functional unit (1 MWh) basis. Note that the biogenic CO_2 emissions associated with biofibre combustion are not included in the LCA analysis and are accounted for in the forest carbon modelling. Table 37 and Figure 29 summarize the LCA GHG emissions for each bioenergy scenario and the coal reference case. As stated above, these LCA GHG emissions exclude biogenic CO2 emissions associated with biofibre combustion and the results can be interpreted as if carbon neutrality of biomass is assumed.

Table 37. LCA GHG emissions – bioenergy scenarios and coal reference case

GHG emissions (tonnes CO2e / MWh)	Commissioning	Fuel Procurement	Coal combustion	Power Plant	**Total**
Bioenergy Scenario A	0.01781	0.09198	0	0.02183	0.13162
Bioenergy Scenario B	0.00901	0.05479	0	0.02183	0.08563
Bioenergy Scenario C	0.00228	0.07143	0.4235	0.01419	0.51144
Bioenergy Scenario D	0.00116	0.04772	0.4235	0.01419	0.48660
Bioenergy Scenario E	0.01366	0.04748	0	0.02199	0.08312
Bioenergy Scenario F	0.00007	0.03709	0	0.00964	0.04680
Coal	0.00719	0.03538	1.2101	0.00075	1.25340

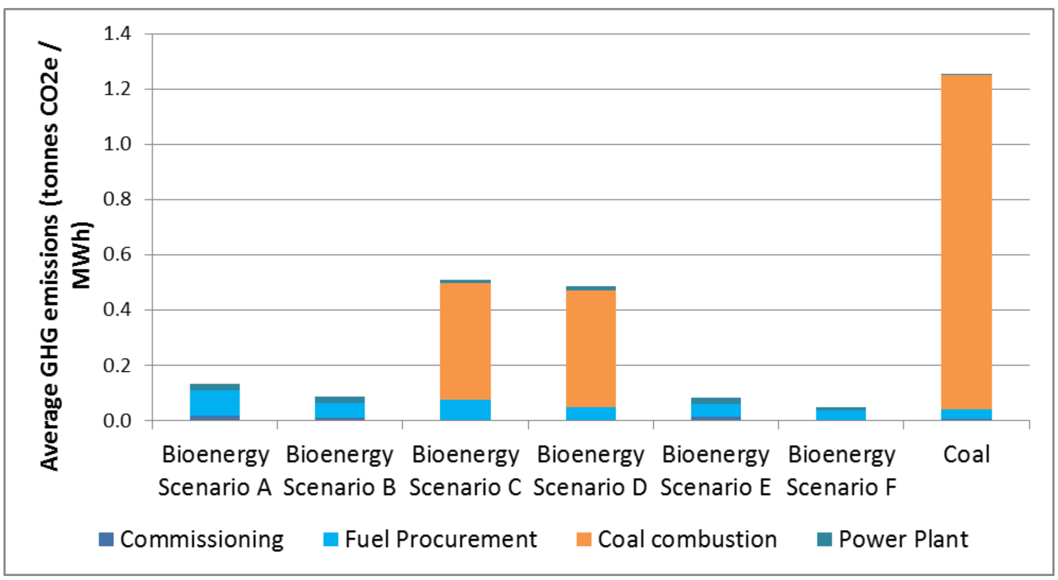


Figure 29. LCA GHG emissions

Note: The GHG emissions in Figure 29 can be interpreted as the GHG emissions when carbon neutrality is assumed and the CO_2 emissions from biofibre combustion are instantaneously resequestered by the forest.

It can be seen in Figure 29 that all bioenergy scenarios have a GHG / MWh intensity significantly lower than the coal reference case. Bioenergy scenario C and D do have a higher GHG / MWh that the other bioenergy scenarios because of the 35% coal co-fire used in these two scenarios.

Generally, the GHG / MWh for bioenergy scenarios A, B, E and F are between 4% and 10% of the coal reference case.

These GHG emissions results are in-line with other biomass LCA studies[80,81,82,83], even though the boundaries of each study vary slightly.

4.3.4 Combining LCA GHG emissions and forest carbon

To get an understanding of the overall GHG emissions, the annual LCA GHG emissions and the GHG emissions resulting from the change in total forest carbon are added together. This quantification framework (as described in Section 2.3) gives an overall appreciation of the GHG emissions of the bioenergy scenarios when taking forest carbon into account.

Figure 30, Figure 31 and Figure 32 summarize the GHG / MWh for bioenergy scenario A (harvesting of hardwood trees – 100% white pellet combustion), bioenergy scenario C (harvesting of hardwood trees – co-fire 65% white pellet combustion) and bioenergy scenario E (utilizing slash – 100% brown pellet combustion). These three scenarios were chosen because they represent each end of the spectrum of the biofibre resource choices, and a mid-point scenario. The GHG emissions from the other bioenergy scenarios are included in Appendix E.

Bioenergy scenario A

The GHG emission rate (tonnes CO_2e / MWh) from full tree harvesting is initially high in the planning horizon compared to the coal reference case. Not until approximately 2060 does the GHG emission rate from biofibre equal the GHG emission rate from coal. As the annual harvesting continues, the landbase sequesters carbon that was initially removed and the GHG emission / MWh is reduced until approximately 2090 at which point it becomes negative. This trend is in-line with the inflection point in Figure 26 (Section 4.3.1) in the carbon curve for the BH2 scenario. From this point forward, the GHG emission profile is negative until the end of the planning horizon.

---

[80] Zhang et al. 2010. Supporting Information for Life Cycle Emissions and Cost of Producing Electricity from Coal, Natural Gas and Wood Pellets in Ontario, Canada

[81] Pa. 2008. Development of British Columbia Wood Pellet Life Cycle Inventory and its Utilization in the Evaluation of Domestic Pellet Applications

[82] Itten et al. 2011. Life Cycle Assessment of Burning Different Solid Biomass Substrates

[83] Magelli et al. 2008. An environmental impact assessment of exported wood pellets from Canada to Europe

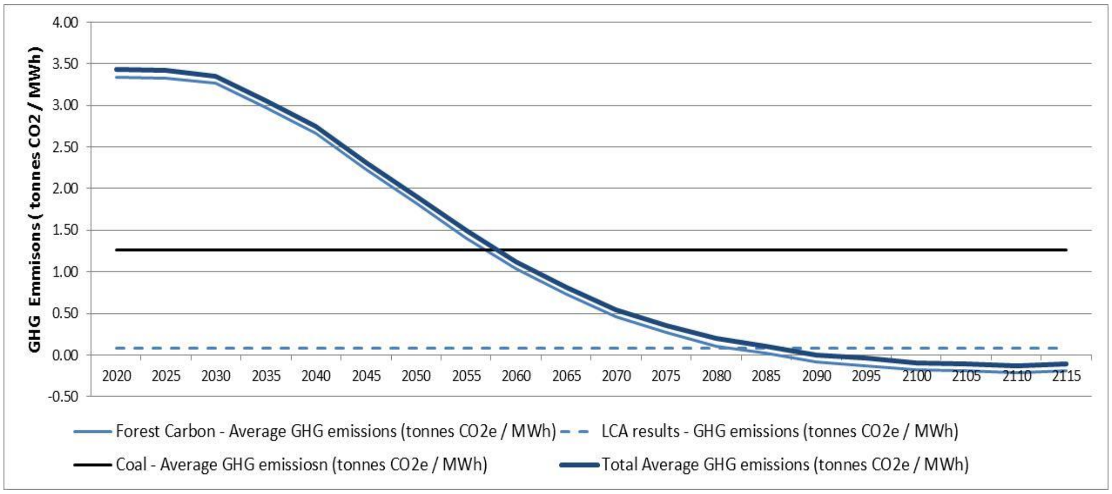


Figure 30. Bioenergy scenario A GHG emissions – Forest Carbon GHG emissions combined with LCA GHG emissions

Bioenergy scenario C

The GHG emission rate (tonnes CO_2e / MWh) from the co-fire scenario is also initially high in the planning horizon compared to the coal reference case, but scaled based on the co-fire percentage of the biofibre and the coal portions. Similar to above, as the annual harvesting continues, the landbase sequesters carbon that was initially removed and the GHG emission / MWh is reduced until 2095 at which point it becomes negative. Overall, the total GHG emissions (tonnes CO_2e / MWh) follow the same trend and profile as Scenario A.

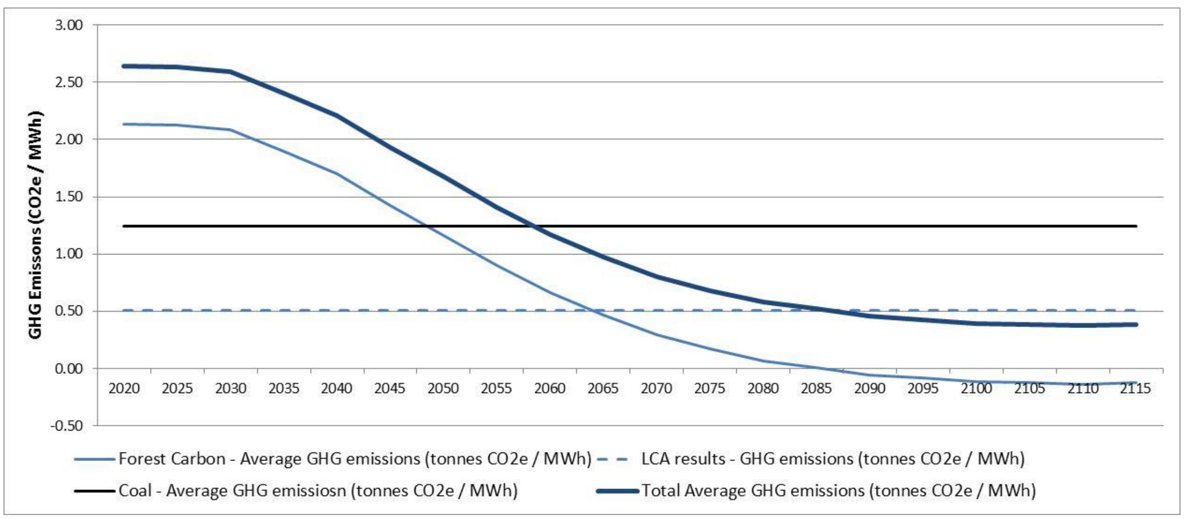


Figure 31. Bioenergy scenario C GHG emissions – Forest Carbon GHG emissions combined with LCA GHG emissions

Bioenergy scenario E

The GHG emission rate (tonnes CO_2e / MWh) from utilizing roadside slash is lower compared to the coal reference case and declines even further along the planning horizon. This trend is in-line with the carbon profile for BH1 in Figure 26. This lower GHG emission profile is attributed to the fact that the biofibre is being sourced from roadside slash which will decompose over time and some of this slash is assumed to be burned in the BH0 baseline scenario.

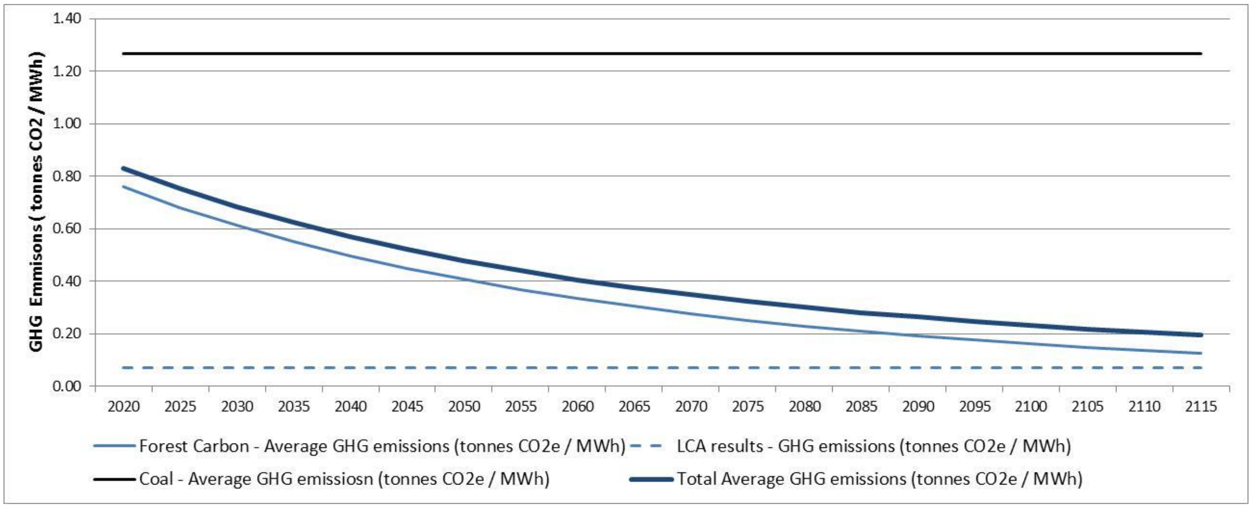


Figure 32. Bioenergy scenario E GHG emissions – Forest Carbon GHG emissions combined with LCA GHG emissions

Table 38 and Figure 33 summarize the total GHG emission rate for each bioenergy scenario and the coal reference case. Note that since the GHG emissions from the forest carbon component are time dependent over the 100 years, the 100-year average GHG emission rate is used.

Table 38. Total GHG emission rate – Bioenergy scenarios and coal reference case

GHG emissions (tonnes CO2e / MWh)	Commissioning	Fuel Procurement	Coal combustion	Power Plant	Forest Carbon	**Total**
Bioenergy Scenario A	0.01781	0.09198	0	0.02183	1.13256	1.26418
Bioenergy Scenario B	0.00901	0.05479	0	0.02183	1.02451	1.11014
Bioenergy Scenario C	0.00228	0.07143	0.4235	0.01419	0.72236	1.23380
Bioenergy Scenario D	0.00116	0.04772	0.4235	0.01419	0.65345	1.14004
Bioenergy Scenario E	0.01366	0.04748	0	0.02199	0.35574	0.43886
Bioenergy Scenario F	0.00007	0.03709	0	0.00964	0.35574	0.40254
Coal	0.00719	0.03538	1.2101	0.00075		1.25340

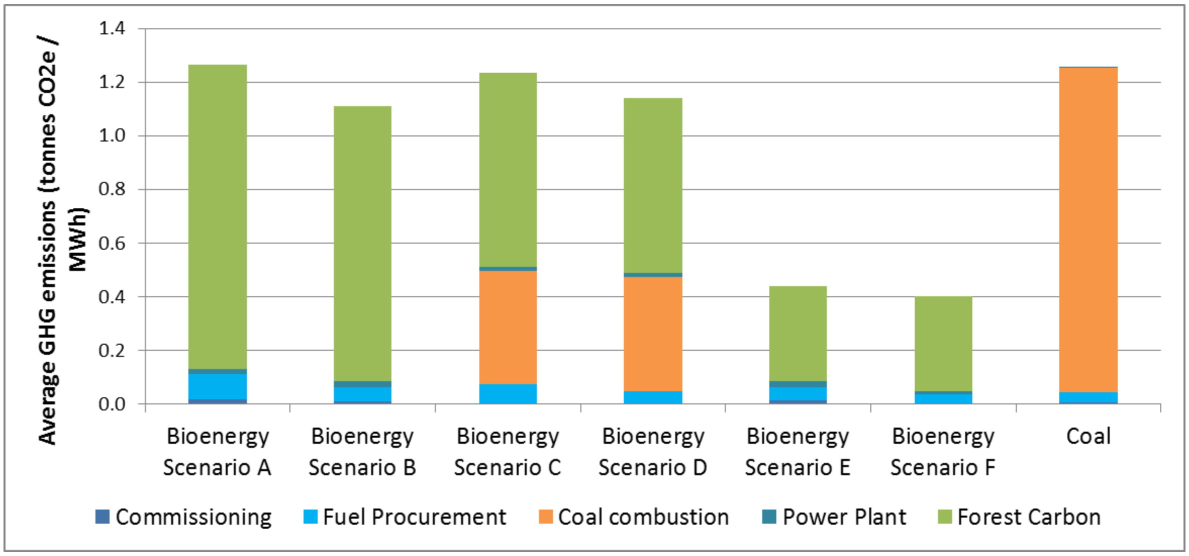


Figure 33. Average GHG emissions over the 2015 – 2115 modelling timeframe – Forest carbon and LCA GHG emissions

Notes: The GHG emissions in Figure 33 can be interpreted as the GHG emissions when carbon neutrality is not assumed but rather the GHG emissions for biofibre combustion and the change in forest carbon are included in the carbon accounting.

The GHG emissions from the forest carbon are time dependent over the 100-year planning horizon and hence the 100-year average has been used.

It can be seen in Figure 33 that when the GHG emissions from the forest carbon component is included, the total average GHG emission (tonnes CO_2e / MWh) from full-tree harvesting (bioenergy scenarios A, B) are approximately the same as the coal reference case (with bioenergy scenario B being slightly less than the coal reference case). For the co-fire scenarios, the average GHG emissions are very similar to their 100% scenario (with only minimum changes due to increased power plant efficiency for the co-fire scenarios); this is because the GHG emission rate for the biofibre portion is very similar to the coal reference case and replacing biofibre with coal only slightly changes the results. For Bioenergy scenarios E and F that utilize slash, the total average GHG emissions are about 66% less than the coal reference case, even when the forest carbon component is added in.

It should be reiterated that Figure 33 summarizes the average GHG emission rate over the 100-years. As shown in Section 4.3.4, the GHG emission rate for the bioenergy scenarios A, B, C and D are significantly higher than the GHG emission rate of coal because of the initial carbon debt that is incurred from harvesting the hardwood species. The impact of this is that the overall GHG emissions for these bioenergy scenarios will be initially higher than coal, and this is discussed in the next section.

4.3.5 Cumulative GHG emissions

To understand the overall GHG emission impacts and when the bioenergy scenarios can be considered to have less GHG emissions compared to coal, the cumulative GHG emissions for each bioenergy scenario are calculated relative to the coal reference case.

Figure 34, Figure 35 and Figure 36 summarize the cumulative GHG emissions for bioenergy scenario A (harvesting of hardwood trees), bioenergy scenario C (co-firing using hardwood trees) and bioenergy scenario E (utilizing slash). The GHG emissions from the other bioenergy scenarios can be found in Appendix E.

Bioenergy scenario A

When using white pellets for 100% electricity combustion, there is initially a positive and increasing source of GHG emissions relative to coal until approximately 2060 at which point the GHG emissions begin to decline. At the end of the planning horizon, there is a small net increase of 0.5 Mt CO_2e relative to coal.

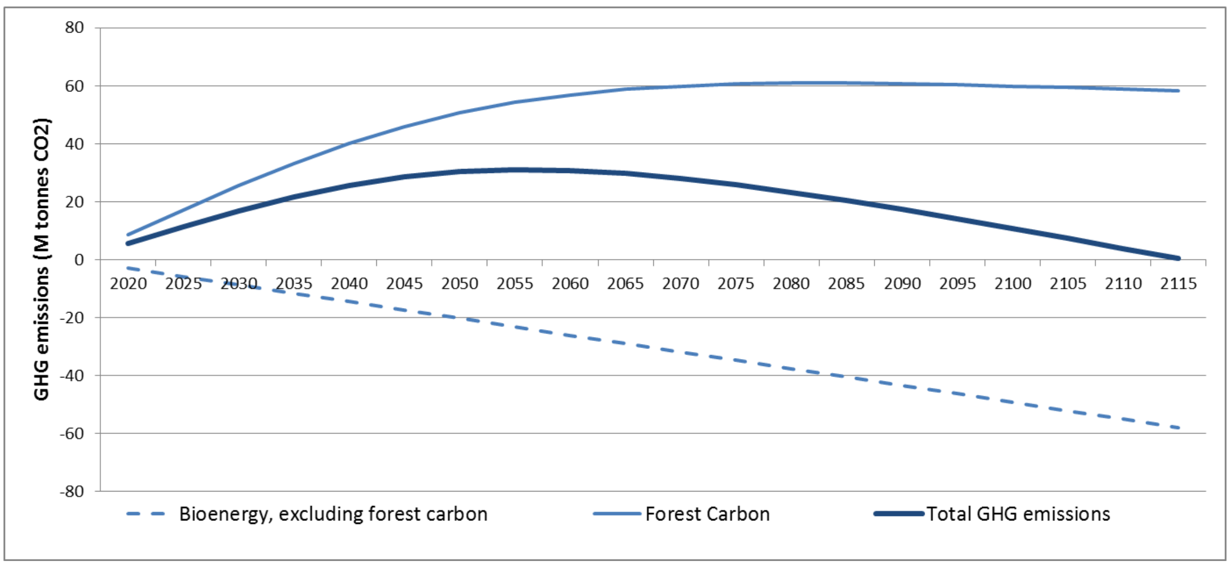


Figure 34. Bioenergy scenario A - Cumulative GHG emissions

Bioenergy scenario C

When co-firing, there is no significant advantage in terms of cumulative GHG emissions. There is only a marginal net reduction of 1.6 Mt CO_2e relative to coal, which is attributed to the small increase in plant efficiency when considering co-fire (32% power plant efficiency for co-fire as opposed to 31.4% plant efficiency for 100% biomass).

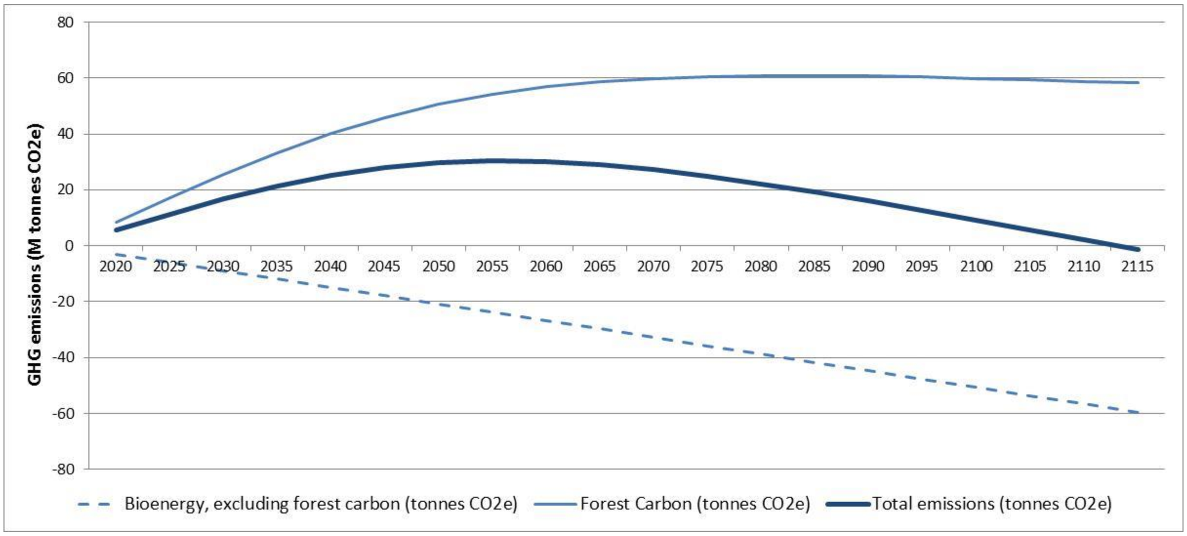


Figure 35. Bioenergy scenario C - Cumulative GHG emissions

Bioenergy scenario E

In the case where brown pellets are utilized for 100% electricity combustion, there is an immediate and significant net reduction of GHG emissions relative to coal. At the end of the planning horizon, there is a net reduction of 56 Mt of CO_2e relative to coal.

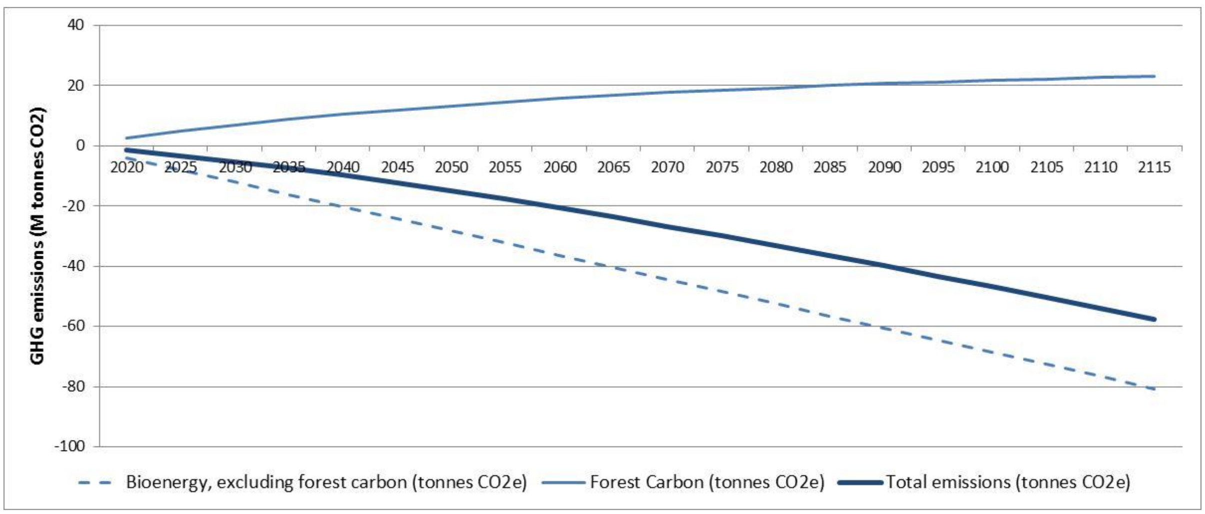


Figure 36. Bioenergy scenario E – Cumulative GHG emissions

4.4 Landscape-level biodiversity indicators

The landscape-level biodiversity indicators studied in this work attempt to combine life cycle thinking and methodologies with more complicated environmental indicators. Although the seven ReCiPe environmental impacts selected for this work converge to the *ecosystem quality* damage category which is also a representation of biodiversity, the three additional biodiversity indicators selected paint an initial story of the effects of biofibre harvesting and extraction.

The three landscape-level impacts quantified for each biofibre harvest scenarios are relative to BH0. For a qualitative discussion on these forest-based landscape-level impacts compared to open-pit coal mining, refer to Section 4.4.4.

The following sections summarize the three landscape-level indicators results. For full documentation on the quantification of the landscape level biodiversity impacts, refer to the report that accompanies the landscape-level modelling.[84]

4.4.1 Biofibre harvest Scenario 1 (BH1)

Since the BH1 scenario looks at utilizing existing available roadside slash without increasing the annual harvest rate, there will be no difference in the seral stage distribution between BH1 and BH0. Therefore, seral stage is not applicable for the BH1 biofibre harvest scenario.

There are no additional new main forestry roads required explicitly for BH1. All the new main roads are required for the future planned harvesting defined in BH0 and these new roads from the traditional forest industry and have been included in the fragmentation modelling for BH0. Therefore, fragmentation is not applicable for the BH1 bioharvest scenario.[85]

No additional CWD is created in BH1 relative to BH0 since there is no increase in the annual harvest rate. Therefore, CWD is not applicable for the BH1 biofibre harvest scenario. (For the definition of CWD used in this analysis, refer to Section 3.9.3)

4.4.2 Biofibre harvest Scenario 2 (BH2)

As presented in Section 2.2.2.1, the average % increase of the AAC for bioharvest scenario for the four FMUs within the landbase is 75%.

4.4.2.1 Seral Stage Distribution

While the BH2 harvest level is constant over the forecast period, we observe an increasing amount of stands aged less than 21. This occurs because of the model targets the oldest eligible stands first which tend to carry the highest volume density (volume/ha). Over time, the average age of harvest declines and thus the standing volume per hectare also declines and resulting in an increasing rate of area harvested in order to satisfy the constant volume target. This change in rate is apparent at year 50 of the forecast as shown in Figure 37. By the end of the forecast, the area of early seral forest in BH2 exceeds BH0 by approximately 377,000 ha or 41% higher.

The periodic “jaggedness” of the seral stage area forecasts is due to two factors. First, natural disturbance is simulated on the landscape and while it is forecast to occur at a steady rate by forest type, it is not age dependant and therefore does not happen evenly. This, along with artifacts associated with 20 year age classes contributes to the unevenness of the line.

As seen in Figure 38, this change in harvest age is very evident. For approximately the first 60 years of the forecast, the BH2 volume target is satisfied by stands older than 60 years of age. We

---

[84] Internal EC report, *An Assessment of Key Landscape Components as a Supplement to the Life cycle Analysis Expertise for Bioenergy Production Project*, Unpublished. The Silvatech Group, 2012.

[85] This is a departure from the allocation of main roads for bioenergy scenarios E and F in BH1 but the integration of LCA allocation procedures for seral stage distribution could not be completed for this first iteration.

observe a slight increase in the amount of forest aged 41–60 between year 45 and 60 because from the beginning of the forecast, the harvest level in BH2 is greater than BH0. This results in more stands entering the 41–60 year age class, 40 to 60 years from today. However, by year 60, in order to sustain the increased harvest target, more stands must be harvested in the 41–60 year age group for the remainder of the forecast period. The difference is quite dramatic over the last 40 years of the forecast — by the end of the 100-year planning horizon, the area of mid seral forest in BH2 is 370,000 hectares (67%) less than in BH0.

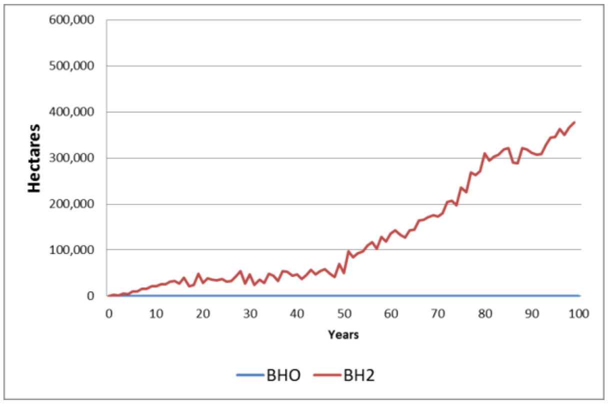


Figure 37. Early-seral comparison of BH2 relative to BH0

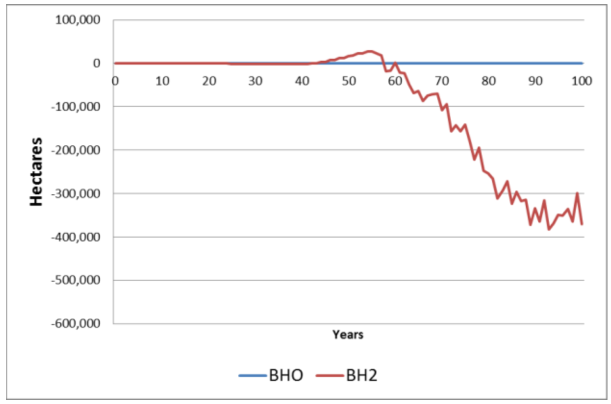


Figure 38. Mid-seral comparison of BH2 relative to BH0

Similar to the pattern observed in the mid-seral age class, we see the onset of increased harvest effects in BH2 about 20 years earlier in the early old-seral stage. Again, this orderly reduction in area by age class is driven largely by the oldest-first harvest queue. While these stands are rationed longer and not harvested intensively until 60–70 years into the forecast in BH0, they are harvested sooner in BH2 in order to satisfy the increased harvest target, as shown in Figure 39.

Merchantable forest older than 140 years old is not prominent on the current landscape, occupying only 1.4% of the current merchantable forest area. The application of the oldest-first harvest queue effectively eliminates this age class from the merchantable and available forest within the first 25 years of the planning horizon. The old forest that remains is almost exclusively white and red pine-dominated stands which are avoided for harvest according to objectives defined in the FMPs.

It is important to note that other vegetation types not scheduled for harvest are not included in this summary. For example, treed swamp will have many forest characteristics and does contribute to the overall age structure of the landscape. However, since these areas are not changed between scenarios and the focus of this analysis is on the difference in BH2 and BH3 from BH0, these areas are not highlighted here.

As seen in Figure 39, there is no real difference in BH2 relative to BH0 in the amount of old forest for the first 60 years. Because the harvest target in BH0 is less than BH2 in all periods, not all of the forest aging into the old seral class about 60 years into the forecast is required to be harvested immediately as it is in the BH2 scenario. However, these stands are only rationed about 20 years longer in BH0 before they enter the harvest queue and the balance of old forest excluding red and white pine-dominated types returns to zero. It is also important to remain mindful that almost all of the white and red pine dominated stands aging through the forecast and many into the old seral category because they are not available for harvest because of habitat constraints. However, since this is consistent across scenarios, it is not apparent in the scenario comparison graphs.

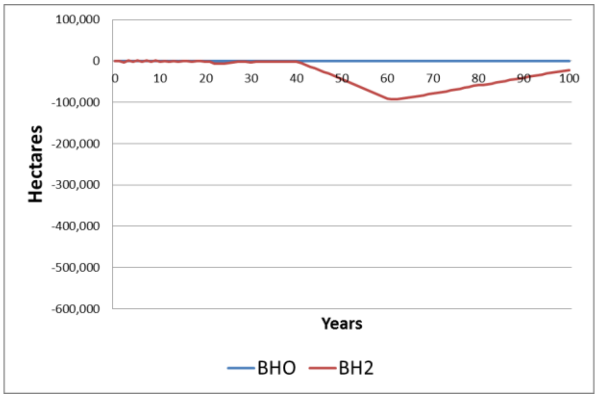


Figure 39. Early old-seral comparison of BH2 relative to BH0

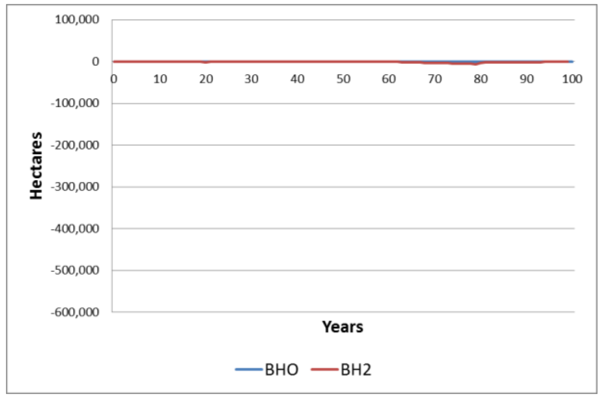


Figure 40. Old-seral comparison of BH2 relative to BH0

4.4.2.2 Forest Fragmentation

As was noted earlier, in-block (tertiary) haul roads associated with BH2 and BH3 incremental harvesting are assumed to have a lifespan of 20 years – after which it is assumed that forest regeneration reclaims these features from the landscape. Similarly, edge from cutblocks and burned areas is assumed to only persist for the first 20 years following harvest, after which it is assumed that successful regeneration has eliminated perceptible stand edge.

There are two new edge differences in BH2 relative to BH0. First, it is assumed 371 km/year of in-block roads with a 20-year lifespan are necessary[86] in BH2 in order to access the additional biofibre volumes defined by the BH2 harvest levels. Secondly, additional forest area is harvested in BH2 leading to a greater active cutblock area in BH2 relative to BH0.

Figure 41 shows the difference in edge (expressed as a density measure of kilometres per square kilometre) associated with tertiary roads and cutblock edge. Similar to the dynamic observed in early seral stage area, more and more area must be harvested per year to satisfy a constant harvest target over the planning horizon, which results in a growing rate of increase in polygon edge density in this forecast. Compared with BH2, Figure 42 shows that by year 50, edge density is roughly 25% greater; it peaks at approximately 73% greater at the end of the planning horizon.

[86] The 371 km/year of in-block roads was derived from information provided by FPInnovations based upon the volume of material forecast to be removed.

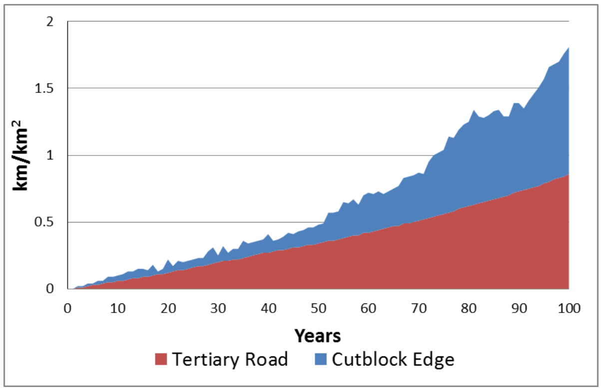


Figure 41. BH2 Actual edge density relative to BH0

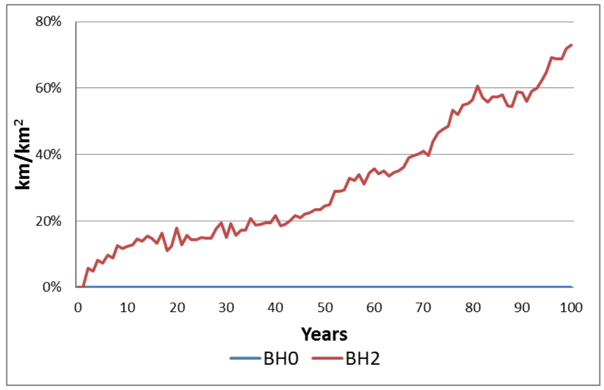


Figure 42. BH2 percent change in edge density relative to BH0

As a visual reference, Figure 43 shows an approximated example of what 1.5 km/km^2 of edge density looks like.

Figure 43. Approximately 1.5 km/km2 edge density conditions found within the study area showing road edge in red and cutblock edge in yellow (picture shows approximately 100 km^2)

Source – Google Earth

The edge density in this photograph was not computed using GIS but is an ocular estimate for illustrative purposes only. An actual edge density measurement using remote sensing tools would be valuable for understanding current conditions and to provide a more precise starting point for forecasting.

4.4.2.3 CWD

Figure 44 illustrates the CWD forecast for BH0 and the relative contribution of Decay and Accumulation components. Over the planning horizon, the amount of accumulation CWD decreases as mature forest is harvested and the landbase approaches a regulated state. It is logical that as old forests are harvested and the forest age class distribution becomes more normalized, the amount of accumulation debris will decrease over time. Conversely, harvest activity results in an increasing amount of decay debris as more of the forest is converted to early- and mid-seral stands.

The trend of declining accumulation debris and increasing decay debris observed in BH0 also holds true in BH2, as seen in Figure 45. However, we do observe that the rate of decline in accumulation and the rate of increase in decay are greater in this scenario compared with BH0. This is intuitive as the elevated harvest target of BH2 converts the forest to a younger state faster than was achieved in BH0.

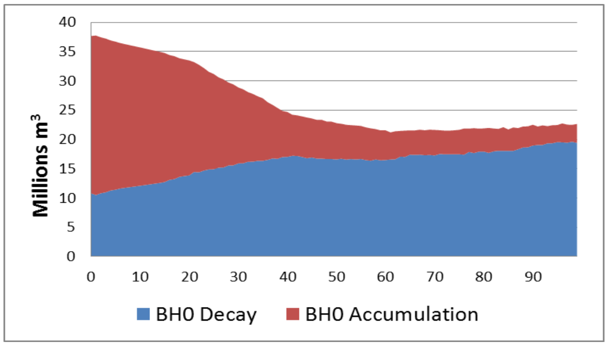


Figure 44. CWD by decay and accumulation components for BH0

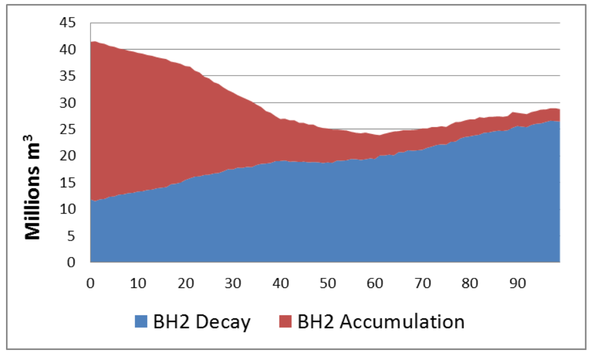


Figure 45. CWD by decay and accumulation components for BH2

Figure 46 illustrates the relative change between BH2 and BH0 by for each component phase. By and large, the decay component increases slowly over the first 50 years of the forecast but then increases more rapidly over the last 50 years. This is associated with the increasing rate of harvest area needed to be harvested in the latter stages of the forecast in order to meet the harvest target from an ever younger and younger forest. The difference peaks at the end of the forecast roughly 45% higher than BH0. We can also see the effects of the increased harvest target on the accumulation side as the rate of harvest of old stands is greater in BH2 than BH0. Because the older stands where accumulation of debris is greatest is rationed longer in BH0 than BH2, we see a fairly sharp decline in the first 40 years of the planning horizon. However, in the latter half of the planning horizon, the older forests are also eventually harvested in BH0 and we see the rate of decrease in accumulation debris reduced through this time period.

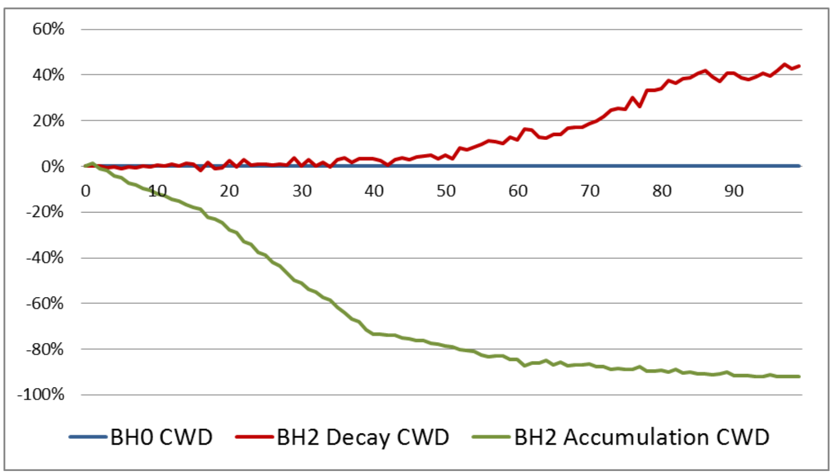


Figure 46. Percent change of CWD by decay and accumulation phase in BH2 relative to BH0

4.4.2.4 Summary

Overall, the implications of the BH2 forecast relative to BH0 are greatest in the long term. Over the first 10 years of the forecast the primary difference observed is an 11% reduction in early-old seral forest area (< 0.1% of the forested area) and a 12% increase in road and block edge (0.1 km/km^2). In the long-term, we observe significant differences in all age classes except those older than 140 years of age. Early seral, mid seral and early-old seral classes change by +41%, -67% and -87%, respectively. Similarly, BH2 road and block edge is 73% greater in year 100 than in BH0. Coarse woody debris changes in composition over time from being dominated by accumulation phase debris to decay phase debris. Of particular note is a 92% decline in accumulation phase debris relative to BH0 at year 100.

Table 39. Summary of landscape-level impacts for BH2

Metric	**Attribute**	**Short term (10yrs)**		**Mid-term (50 yrs)**		**Long-Term (100 yrs)**	
		Actual △	(%)	Actual △	(%)	Actual △	(%)
Forest Seral Stage (ha)	Early (0-20yrs)	20,784	4	69,671	9	377,198	41%
	Mid (41-60 Yrs)	-184	0	17,397	3	-370,673	-67%
	Early Old (121-140 Yrs)	-2,063	-11	-43,723	-80	-21,657	-87%
	Old (141+ Yrs)	-177	-1	0	0	-640	-2
Fragmentation (km/km^2)	Road/block Edge	0.1	12	0.48	24	1.81	73
Coarse Woody Debris	Decay Stage		1		5		44
	Accumulation Stage		-12		-78		-92

25% - 49 % △Compared to BH0	50% - 74 % △Compared to BH0	75% + △Compared to BH0

4.4.3 Biofibre harvest Scenario 3 (BH3)

As presented in Section 2.2.2.1, the average % increase of the AAC for bioharvest scenario for the four FMUs within the landbase is 95%.

4.4.3.1 Seral Stage

The landscape dynamics driving BH3 results are similar to those observed in BH2 but to a more pronounced degree associated with the further increases in volume harvested.

As with BH2, while the BH3 harvest level is constant over the 100-year forecast period, we observe an increasing amount of stands aged less than 21 years as shown in Figure 47. Since the model selects the oldest eligible stand in each FLB in each year to harvest until the constant volume target is met, the age of harvest generally declines through the planning horizon and as a consequence volume per hectare at harvest also declines. In general, more and more area must be harvested to satisfy the constant volume queue. This is not as smooth a trend as was observed in BH2 and the difference is likely due to the initial age class distribution of the forest as a whole and the differences in the rate of harvest. By year 100 of the forecast, the area of early seral forest in BH3 exceeds BH0 by approximately 562,570 ha or 61% higher.

Figure 48 shows that the BH3 volume target is satisfied by stands older than 60 years of age for only the first 40 years of the forecast (one-third less time than in BH2). Harvesting in this profile is significant and drives down the remaining mid-seral age class forest by some 450,000 ha compared with BH0 by year 80 (approximately 65% reduction). There is resurgence in the area of mid-seral forest in the last two decades as much of the forest harvested in the first 20 years is aging into this seral category. By the end of the forecast there are roughly 305,000 hectares (approximately 55%) less forest in this age class than in BH0 by year 100 but approximately 65,000 ha more than BH2 at the same time period.

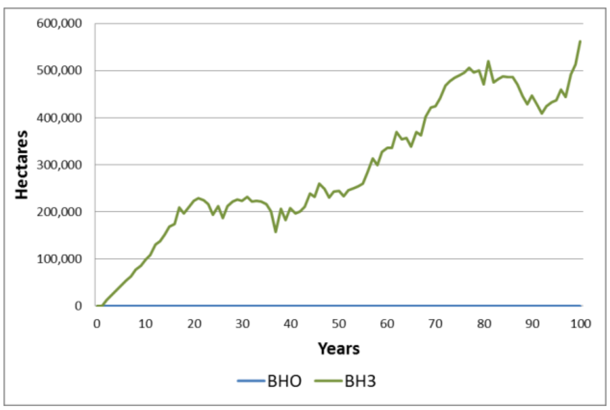


Figure 47. Early-seral comparison of BH3 relative to BH0

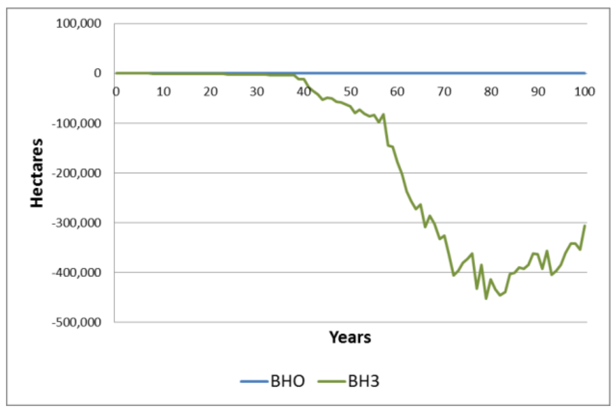


Figure 48. Mid-seral comparison of BH3 relative to BH0

Similar to the pattern observed in BH2, we observe a sharp decline in stands aged 121–140 around year 40 of the forecast though more harvesting is occurring in this age class earlier than in BH2. Again, this orderly reduction in area by age class is driven largely by the oldest-first harvest queue. The forecast area for stands older than 140 is largely the same as in BH2. These trends are seen in Figure 49 and Figure 50.

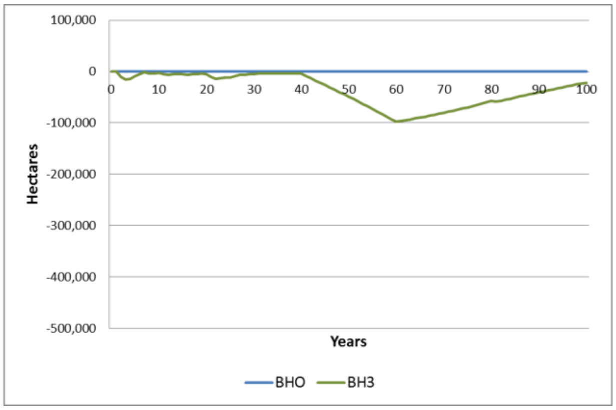


Figure 49. Early-old seral comparison of BH3 relative to BH0

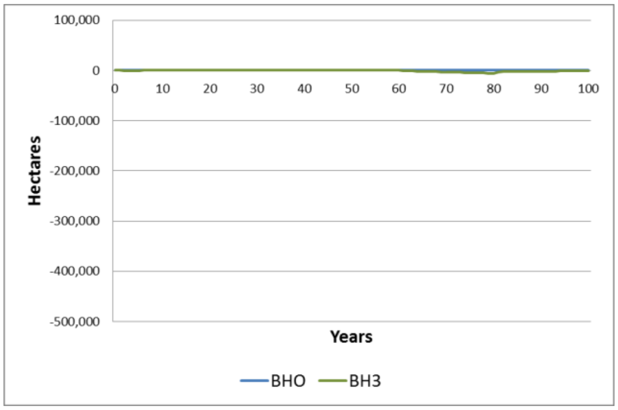


Figure 50. Old-seral comparison of BH3 relative to BH0

4.4.3.2 Forest Fragmentation

There are also two new edge differences in BH3 relative to BH0. First, it is assumed 734 km/year of in-block roads are necessary in BH3 in order to access the additional biofibre volumes defined by the BH3 harvest levels. Secondly, additional forest area is harvested in BH3 leading to an even greater active cutblock area and associated edge in BH3 relative to BH0.

Figure 51 shows the difference in edge (expressed as a density measure of kilometres per square kilometre) associated with tertiary roads and cutblock edge.. Similar to the dynamic observed in early seral stage area, more and more area must be harvested per year to satisfy a constant harvest target over the planning horizon, which results in an increasing rate of increase in polygonal edge density in this forecast. Compared with BH3, Figure 52 shows that by year 50, edge density is roughly 69% greater; it peaks at approximately 134% greater at the end of the planning horizon.

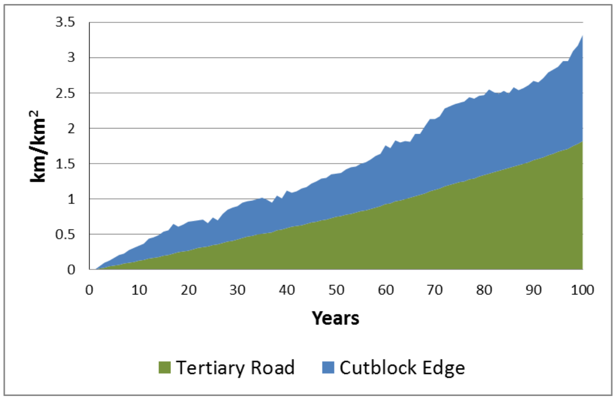


Figure 51. BH3 Actual edge density relative to BH0

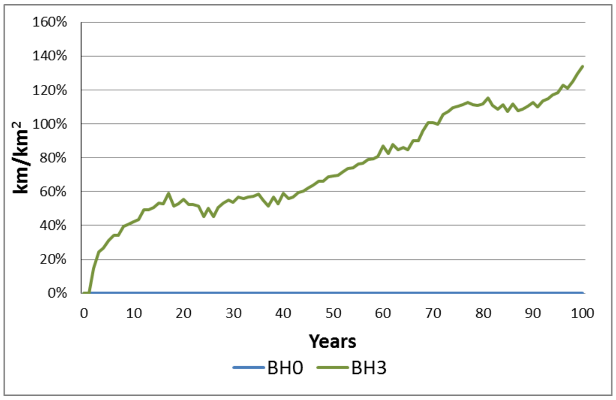


Figure 52. BH3 percent change in edge density relative to BH0

For visual reference, Figure 53 shows an approximated example of what 3.0 km/km2 of edge density looks like.

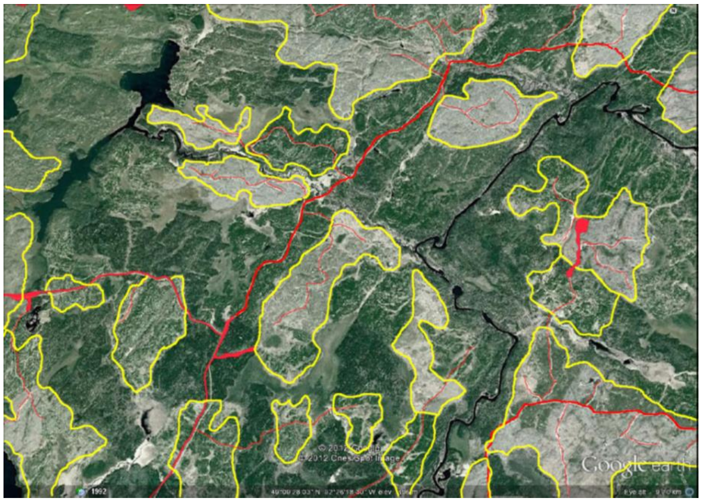


Figure 53. Approximately 3 km/km2 edge density conditions found within the study area showing road edge in red and cutblock edge in yellow (picture shows approximately 100 km^2)

Source – Google Earth

The edge density in this photograph was not computed using GIS but is an ocular estimate for illustrative purposes only. An actual edge density measurement using remote sensing tools would be valuable for understanding current conditions and to provide a more precise starting point for forecasting.

4.4.3.3 CWD

As for BH2, individual models for BH3 for each FLB across each scenario were developed using area-weighted forecasts of slash remaining in the cutblock following harvest as forecasted by the FP Innovations work as the y-intercept. This takes into account the different harvesting systems forecast to be applied to the various ecosystems across the range of harvest scenarios and enables the temporal forecasting of CWD to be calculated by FLB across scenarios according to the age class distribution of the entire forested landscape and for that to be broken down into its component parts (decay and accumulation).

The trend of declining accumulation debris and increasing decay debris observed in BH0 and BH2 also holds in BH3, as seen in Figure 55. As expected, the higher harvest rate also increases the rate of decline in accumulation and increases the volume of decay phase debris compared with BH0 and BH3.

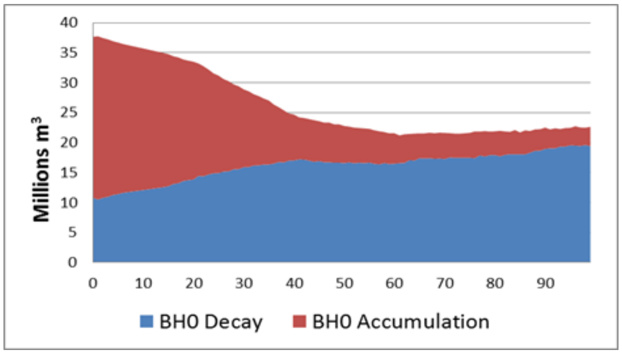


Figure 54. CWD by decay and accumulation components for BH0

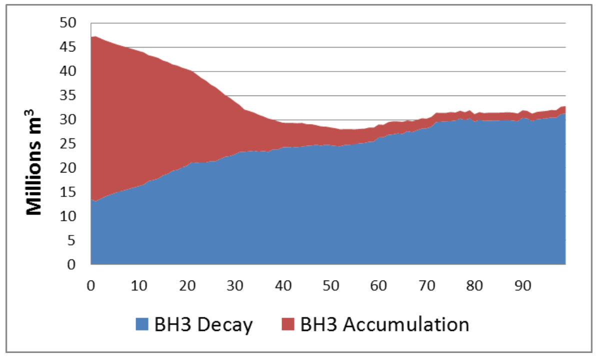


Figure 55. CWD by decay and accumulation components for BH3

Figure 56 illustrates the relative change between BH3 and BH0 by for each component phase. The decay phase debris peaks about 75 years into the forecast roughly 60% higher than in BH0. The decrease in BH3 accumulation phase debris is rapid over the first 40 years and then levels off at roughly 96% below BH0.

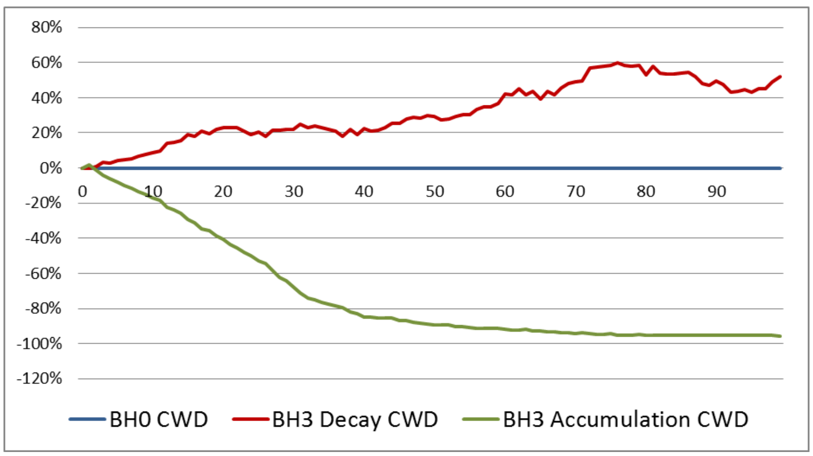


Figure 56. Percent change of CWD by decay and accumulation phase in BH3 relative to BH0

4.4.3.4 Summary

Like BH2, the implications of the BH3 forecast relative to BH0 are greatest in the long term. There is however also significant change in the mid-term as well. Three out of the seven metrics are more than 50% different than BH0 within the first 50 years; two of these are more than 75% different. Fragmentation changes rapidly, with a 42% increase in the first 10 years, peaking at 3.32 km/km^2, roughly 2.3 times that observed in BH0. Accumulation stage CWD is 89% below that observed in BH0 by year 50. Old forest is only slightly changed from BH0 but all other metrics have significantly different performance relative to BH0.

Table 40. Summary of landscape-level impacts for BH3

Metric	Attribute	Short term (10yrs)	Mid-term (50 yrs)	Long-Term (100 yrs)

		Actual △	(%)	Actual △	(%)	Actual △	(%)
Forest Seral Stage (ha)	Early (0-20yrs)	98,657	17	244,704	33	562,570	61%
	Mid (41-60 Yrs)	-438	0	-66,309	-13	-305,472	-55%
	Early Old (121-140 Yrs)	-2,737	-15	-48,878	-90	-21,657	-87%
	Old (141+ Yrs)	-18	0	0	0	-640	-2
Fragmentation (km/km^2)	Road/block Edge	0.34	42	1.36	69	3.32	134
Coarse Woody Debris	Decay Stage		7		30		52
	Accumulation Stage		-17		-89		-96

25% - 49 % △Compared to BH0	50% - 74 % △Compared to BH0	75% + △Compared to BH0

4.4.4 Summary of landscape-level indicators

The measure of risk to biodiversity from change on the landscape can be thought of in terms of the change in the system's ability to experience a disturbance, re-organize and resume the processes that enable it to endure. In both the forestry and coal assessments performed in this work, our management efforts tend to reduce this natural resilience by imposing long term static conditions. While a 'catastrophic' natural disturbance such as a large wildfire can drastically change forest age class distribution, edge fragmentation and the accumulation component of CWD, events like this are fairly rare (fire cycles for the Ontario study area estimated by OMNR from between 366 and 1595 years) and most importantly, the post disturbance conditions do not persist indefinitely.

The difference with human disturbance as assessed in this work through increased harvest rates is that forecast changes are expected to be increasing and persistent – the conclusion is there will be long-term change from the RNV

Though fragmentation can either increase or decrease local biodiversity, some species are adversely affected at a large scale[87,88]. Fragmentation can result in diminished native biodiversity and homogenization of flora and fauna across landscapes (Noss 1983, 1990). Some species will use anthropogenic edges to their advantage; for example, some carnivores may use linear features to facilitate predation (Jordaan, Keith and Stelfox, 2009). Species most likely to be adversely affected by habitat fragmentation include specialist species that require niche habitats (Fahrig 2003) and large carnivores that require extensive tracts of undisturbed habitat (Yahner 1988).

4.4.5 Summary of landscape-level indicators compared to coal mining

While forest management in the biomass scenarios attempts to emulate natural disturbance as much as possible, the coal scenario will completely and permanently change the entire surface landscape ecosystem. Current practice within the biofibre study area will lead to younger forests will that are increasingly fragmented and predominated by decay phase debris with significantly reduced old stand structure. One of the factors that can cause a system to flip to an altered state without much chance to revert is the pace of change. If change happens rapidly it may reduce the opportunity for adaption. Compared to current practice in BH0, BH2 and more so BH3, result in a greatly increased rate of change in addition to an increased magnitude of change. Key aspects of structure and fragmentation are highlighted in this summary because of their rapid and sustained change.

In the surface mine case, localized microsite complexity created by mine spoil dumping has created suitable habitat for a number of species of wildlife and flora that currently occupy the site. However, the site will be completely transformed to a forage / crop mix of vegetation on a gently undulating land form. Biodiversity is expected to be reduced but no quantitative measure is available. It is abundantly clear however that the transformation from a highly irregular microsite dominated by a range of vegetation including shrubs and trees to a gently undulating agricultural landscape is a significant alteration of the structural attributes of the area.

In summary, the mine application area is currently a residual mine spoil disposal site that has been naturally reclaiming over the past few decades. Localized microsite complexity has created suitable habitat for a number of species of wildlife and flora that currently occupy the site. The site will be completely transformed to a gentle sloping agricultural forage / crop mix of vegetation on a gently undulating land form. Biodiversity is expected to be reduced and this is acknowledged in the Environmental Impact Assessment – though no quantitative measure is provided. While vegetation age class and CWD are less suitable attributes in this case, it is noted that the landscape will be transformed from one with a degree of tree and shrub cover to one with perennial grasses and/or an annual cereal crop mix and this will definitely be a significant reduction in structural attributes for most wildlife. The region is heavily fragmented by agriculture and the incremental additions from this mine site will be negligible.

[87] Saunders et al 1991

[88] Wilcove 1987

For more information on the qualitative comparison of open-pit coal mining, refer to the landscape-level sub-project report.[89]

[89] Internal EC report, *An Assessment of Key Landscape Components as a Supplement to the Life cycle Analysis Expertise for Bioenergy Production Project*, Unpublished. The Silvatech Group, 2012.

5. Comparison of potential environmental impacts between different bioenergy scenarios

The following sections highlight and discuss some key and relevant comparisons between the bioenergy scenarios and the difference in potential environmental impacts these bioenergy scenarios offer.

Radar diagrams[90] can be an effective visual tool for comparing between options and scenarios that have multi-dimensions – for this work, there are ten potential environmental impacts that are quantified and contributing to the overall 'outcome' of the bioenergy scenario by observing the area created through the graphing. Although effective, radar diagrams have their limitations. Below is a summary taking into consideration this work

- The 10 radii presented on the radar diagrams are not weighted and have no relation to each other
- The order of the environmental impacts affect the area of the graph – it is not the area or shape of the area of each option, but the difference between the areas
- The maximum scale for each radii is 10 and each radii scaling are independent of each other (i.e. a 10 for climate changes does not mean the same as a10 for terrestrial acidification)
- These graphs do not show the results relative to coal, but rather the absolute emissions are graphed for two scenarios relative to each other. The goal of these graphs is to provide a visual comparison between two bioenergy scenarios.

Because of the challenge of selecting the most appropriate result for the landscape-level indicators (i.e. which seral stage to select) and normalizing these to the LCA's functional unit, only the seven Ecoinvent environmental impact categories (which include forest carbon) are graphed in these radar diagrams and a discussion of the landscape-level indicators is included.

---

[90] http://en.wikipedia.org/wiki/Radar_chart

5.1 Brown pellets vs. white pellets

Understanding the tradeoffs between the production of brown pellets and that of white pellets can be accomplished by comparing the environmental impacts from bioenergy scenario A and bioenergy scenario E, as shown in Figure 57.

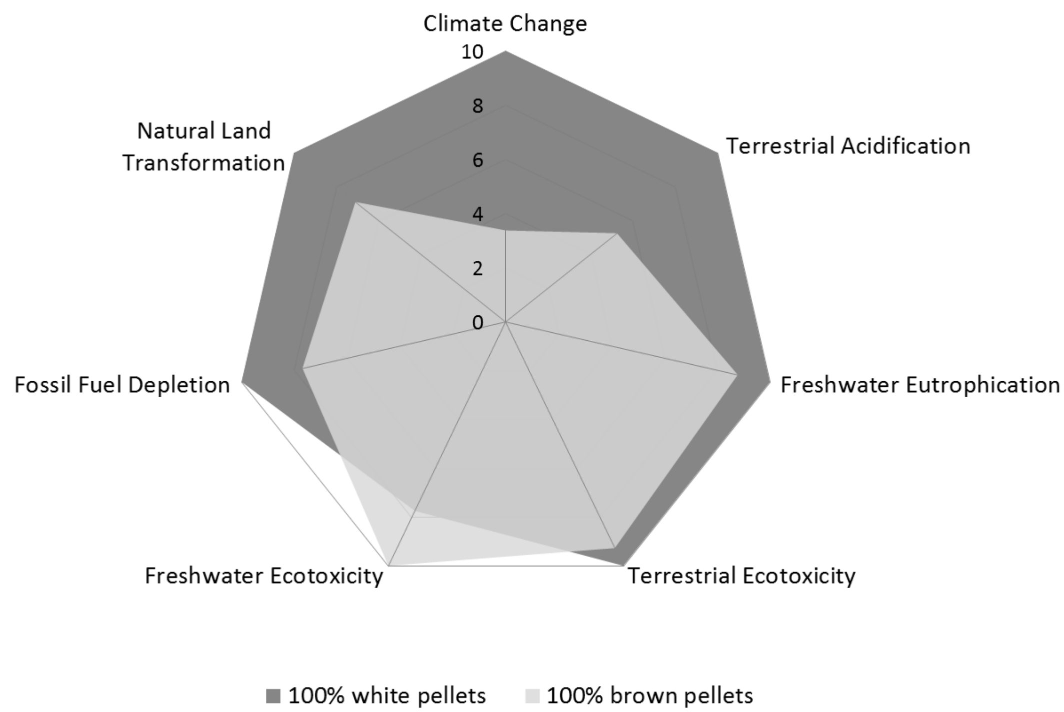


Figure 57. Comparison between brown pellets and white pellets for 100% biofibre combustion

Generally, most of the potential environmental impacts associated with producing and utilizing brown pellets are less than white pellets. Table 41 provides insight into the main differences.

Table 41. Summary of comparison between brown pellets and white pellets

Potential environmental impact	Discussion
Climate change	Reduction in GHG emissions for brown pellets compared to white pellets. Two main sources: • Less GHG emissions from taking available roadside slash, as opposed to harvesting trees. • Forest carbon impacts are not as significant
Terrestrial acidification	Reduction in GHG emissions for brown pellets compared to white pellets: • Fewer forestry activities and NOx / SOx environmental releases from taking available roadside slash, as opposed to harvesting trees

	• Slash is no longer being burned in BH1 and is being utilized. Negative contribution of NOx/SOx from slash combustion
Freshwater eutrophication	Insignificant change
Terrestrial ecotoxicity	Insignificant change
Freshwater ecotoxicity	Increase in freshwater ecotoxicity for brown pellets compared to white pellets because of increased wood ash from brown pellets
Fossil fuel depletion	Generally less natural land transformation and fossil fuel depletion because of fewer forestry activities and fossil fuel consumption
Natural land transformation	
Seral stage	Change in all biodiversity indicators as defined in Section 4.4.2 from brown pellets to white pellets because of the increased harvest rate defined for BH2
Fragmentation	
CWD	

5.2 Repowering vs. co-firing

Understanding the tradeoffs between repowering (100% white pellets) and co-firing (65% white pellets / 35% coal) can be accomplished by comparing the potential environmental impacts from bioenergy scenario A and bioenergy scenario C, as shown in Figure 58.

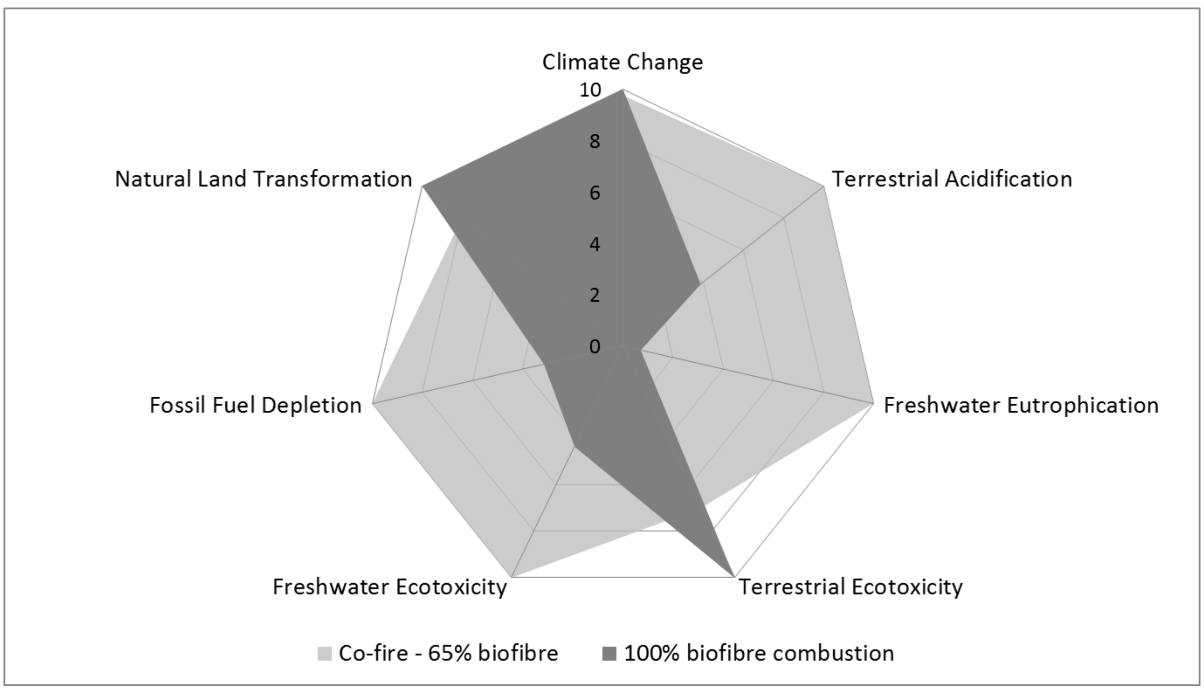


Figure 58. Comparison between repowering and co-firing

Generally, most of the potential environmental impacts associated with repowering (100% biofibre) are less than co-firing. Table 42 provides insight into the main differences.

Table 42. Summary of comparison between repowering and co-firing

Potential environmental impact	Discussion
Climate change	No significant change – GHG emission intensity of white pellets similar to coal when forest carbon is included.
Terrestrial acidification	Decrease in emissions for repowering primarily because of no coal combustion.
Freshwater eutrophication	
Terrestrial ecotoxicity	Slight increase in emissions from repowering because of pellet combustion.
Freshwater ecotoxicity	Decrease in emissions from repowering because of pellet ash
Fossil fuel depletion	Decrease in emissions from repowering with the utilization of biofibre instead of coal
Natural land transformation	Small increase in natural land transformation because of XXX
Seral stage	No change in biodiversity indicators because harvest rate does not change – both bioenergy scenarios utilizing bioharvest scenario BH2.
Fragmentation	
CWD	

5.3 Hardwood chips vs. hardwood logs processing, and increase in % of AAC utilized

Understanding the tradeoffs between different biofibre extraction options and increasing the % of AAC utilized can be accomplished by comparing the potential environmental impacts from bioenergy scenario A and bioenergy scenario B as seen in Figure 59. Table 43 summarizes the extraction / processing differences between hardwood chips and hardwood logs used to make white pellets:

Table 43. Differences between extracting hardwood chips and hardwood logs from the forest

	Hardwood chips (bioenergy scenario A)	Hardwood logs (bioenergy scenario B)
Forest Processing		
% of AAC	75%	95%
In-forest processing of white biofibre	Hardwood species are delimbed, debarked at roadside. White biofibre is chipped using diesel.	Hardwood species are delimbed at roadside. Logs are transported out of forest by truck.

Source of slash used in processing drying	Combination of chipped hardwood species' limbs, branches, bark and tops of trees.	Hardwood bark
Transportation	Transportation of slash in chip trucks.	Transportation of logs in logging trucks
Pellet Plant Processing		
Processing of biofibre	Incoming chips are put through hammermill, dried and pressed. Hammering and pressing uses Ontario grid electricity. Drying of pellets use slash.	Incoming logs are debarked and chipped. Debarking and chipping uses Ontario grid electricity. Chips are put through hammermill, dried and pressed. Hammering and pressing uses Ontario grid electricity. Drying of pellets use bark.

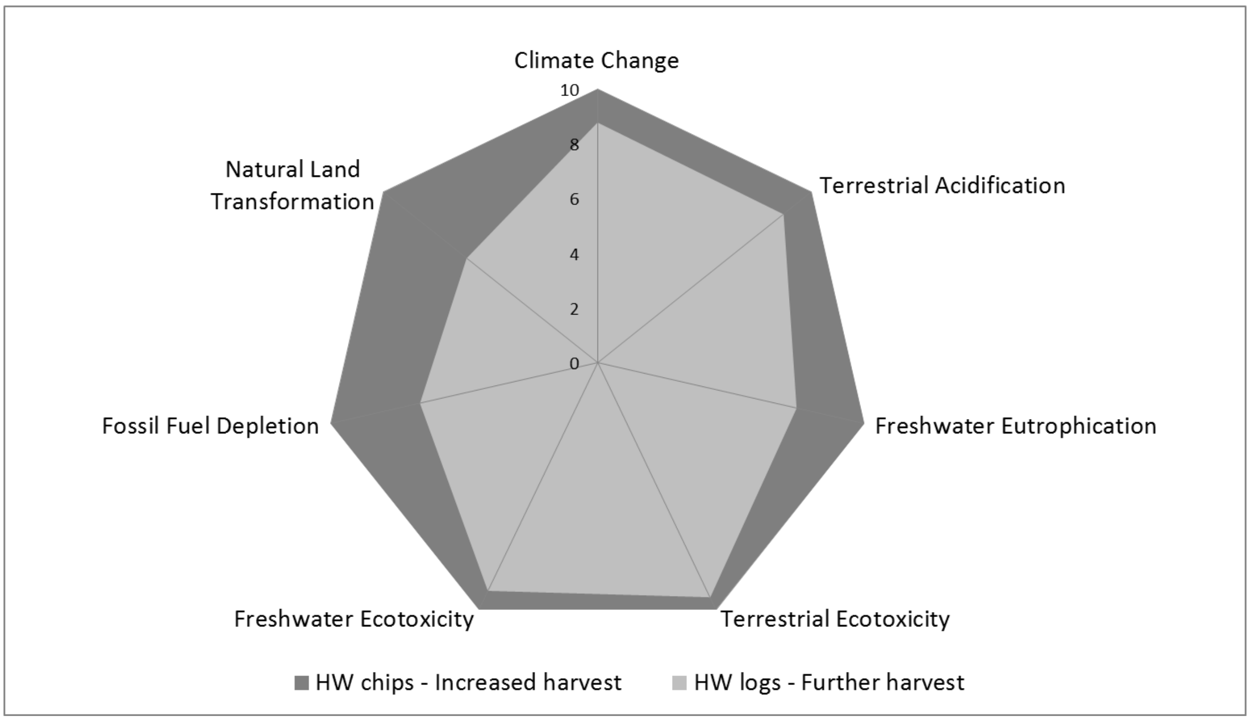


Figure 59. Comparison between hardwood chips and hardwoods, and increasing % of AAC

Generally, all of the potential environmental impacts associated with hardwood chips are less than logs. Table 44 provides insight into the main differences.

Table 44. Summary of comparison between hardwood chips and hardwoods, and increasing % of AAC

Potential environmental impact	Discussion
Climate change	
Terrestrial acidification	

Freshwater eutrophication	
Terrestrial ecotoxicity	
Freshwater ecotoxicity	
Natural land transformation	
Fossil fuel depletion	
Seral stage	Significant change in biodiversity impacts as a result of increasing the % utilization of the AAC
Fragmentation	
CWD	

5.4 Using forestry slash for pellets vs. using roadside slash for CHP

Understanding the tradeoffs between using slash for pellets or for hog fuel can be accomplished by comparing the potential environmental impacts from bioenergy scenario E and bioenergy scenario F as shown in Figure 60. Table 45 summarizes these differences between the extraction and use of slash for pellets and hog fuel:

Table 45. Difference between processing and utilization of slash for brown pellets and hog fuel

	Slash used for chips (bioenergy scenario E)	Slash used for hog fuel (bioenergy scenario F)
Slash processing		
Slash processing	Slash is put through hammermill, dried and pressed. Hammering and pressing uses Ontario grid electricity. Drying of pellets use slash.	Slash is not processed any further. Hog fuel is used as-is.

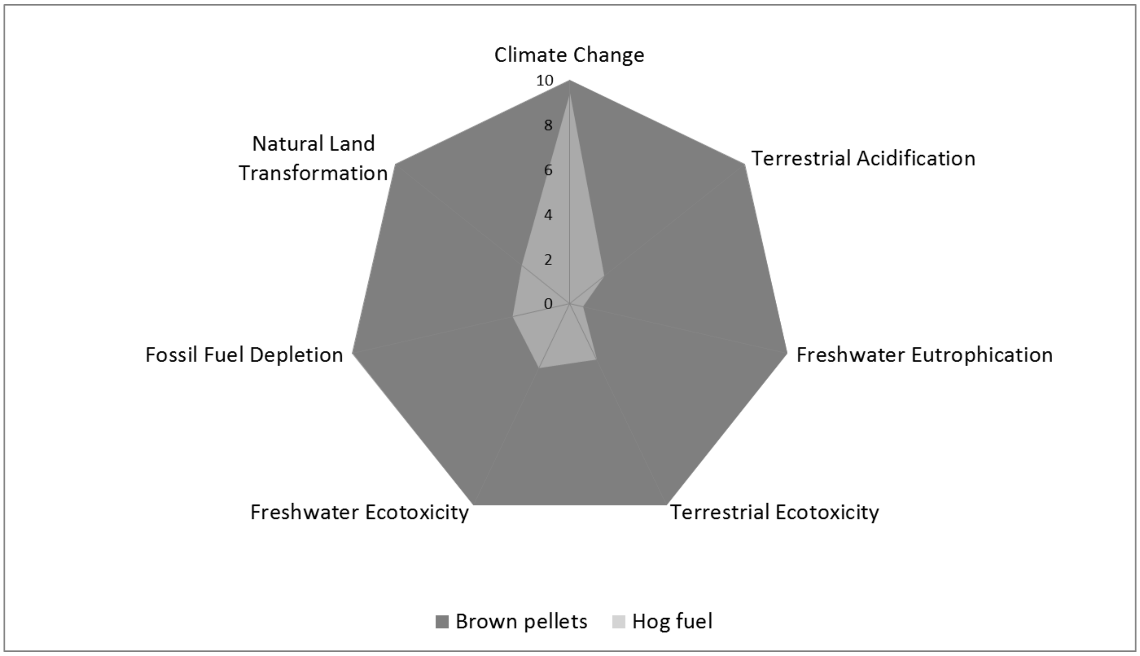


Figure 60. Comparison between brown pellets and hog fuel

Generally, all of the potential environmental impacts associated with hardwood chips are less than logs. Table 46 provides insight into these differences.

Table 46. Summary of comparison between brown pellets and hog fuel

Potential environmental impact	Discussion
Climate change	
Terrestrial acidification	
Freshwater eutrophication	
Terrestrial ecotoxicity	
Freshwater ecotoxicity	
Natural land transformation	
Fossil fuel depletion	
Seral stage	No change in biodiversity indicators since bioharvest scenario is BH1 for both cases.
Fragmentation	
CWD	

6. Uncertainty Assessment and Sensitivity analysis

6.1 Uncertainty assessment

ISO 14044 defines uncertainty analysis as the "*systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability*".[91]

A common LCA uncertainty approach is to acquire standard deviation data for each life cycle stage to estimate data uncertainty of the emission factors and data uncertainty of the activity data. The uncertainty for each data point in the life cycle at all stages are aggregated together to calculate a cumulative effects of data uncertainty and variability for each pathway. Data points can be modified randomly in an iterative fashion and the variability in the results is aggregated together. This is known as a Monte Carlo approach to assess uncertainty.

This approach is not practical in this project for several reasons:

1. Life cycle custom software (i.e. SimaPro) is able to perform a Monte Carlo using built-in functionality. This project has developed a custom Excel-based model so EC can update this work in future without having to purchase an annual custom software license. It is an extremely manually-intensive task to perform a Monte Carlo in an Excel-based model and the project timeline did not allow time for this.
2. This project is using data from subprojects (i.e. FPInnovations, McKechnie et al, coal, landscape-level) and other resources (i.e. Envirochem) where standard deviation values have not been calculated. A large effort would be required to derive standard deviation factors for these projects as it would require extensive communication about these data sources and modelling methodologies that were used.
3. EC is deriving value in identifying datasets (emission factors and activity data) that are the highest priority to update in future work. The project team has adapted a qualitative uncertainty approach, known as a pedigree matrix approach, to assist in this objective.

The pedigree matrix approach has been used for a variety of uncertainty applications as documented by van der Sluijs et al, 2005[92] and van der Sluijs et al, 2003[93]. It indicates a degree

[91] ISO 14044, 2006. Environmental management – Life cycle assessment – Requirements and guidelines.

[92] Van der Sluijs et al. 2005. Combining quantitative and qualitative measures of uncertainty in model-based environmental assessment: The NUSAP System.

of confidence in the results without an overly onerous calculation methodology. This methodology fits with the LCA objectives of a first iteration study. If EC wishes to update the model in future iterations using a quantitative approach, it may be required to obtain statistical software to calculate uncertainty for the results using a Monte Carlo approach.

Uncertainty is expected from the following sources:

1. Data quality (emission factor and activity data)
2. Impact assessment methodology
3. Long-time frame (e.g. effects of climate change on the forest carbon balance, feedstock availability and technology advancements).

The pedigree matrix approach proposed here assesses only the data quality (point #1 above). The scoring system can be seen in Table 47 below and includes four categories that cover the various data dimensions of this project.

Table 47. Pedigree scoring system

	Temporal Representation	Geographical Representation	Technology Representation	Activity Data Certainty
5	<3 years old	Data is from Ontario	Identical technology	Activity data provided by subproject
4	<6 years old	Data is from Canada		
3	<10 years old	Data is from North America	Similar technology	Activity data derived by physical relationshp
2	<15 years old	Data is international		Assumptions made based on physical relationshps
1	>15 years old or unknown	Unknown	Unknown or not similar	Assumption based on intuition

The majority of the uncertainty analysis is performed on the Ecoinvent LCA component of the work as this component has the largest variety of data sources. The two other main modelling components – the forest carbon and the landscape-level have their own datasets and the above pedigree matrix does not completely correlate. A similar qualitative assessment of the forest carbon and landscape-level data is presented at the end of this section.

The overall data quality score of each life cycle calculation is the average of the above four data quality categories (temporal, geographical, technology, activity data). The highest score obtainable is a 5 (i.e. best data quality) and the lowest score is a 1 (i.e. lowest data quality). The pedigree scoring results for each of the four data categories are presented in Appendix G.

Summary tables, shown in Table 48 to Table 54, show the data quality scores against the percentage of life cycle contribution at each life cycle stage. In these tables, each row represents a calculation stage in the life cycle model. Percentage of life cycle contribution values have been highlighted in red when they exceed 10% of life cycle emissions In other words, these are the activities that contribute most significantly to the life cycle results. It is important to note that the pedigree matrix for climate change includes percentage life cycle emissions *without* the

[93] Van der Sluijs et al, 2003. Towards a synthesis of qualitative and quantitative uncertainty assessment: Applications of the numeral, unit, spread, assessment, pedigree (NUSAP) system.

forest carbon component. From the overall GHG results, forest carbon contributes in a range of 57% (for co-firing scenarios) to 90% (for bioenergy scenario A). Forest carbon was intentionally left out from the climate change pedigree analysis so the forest carbon contribution did not overshadow the other life cycle contributions.

The higher the percentage of life cycle, the more important it is to have high quality data. EC should consider the following when updating datasets in future iterations:

- High priority – Activities with high percentage contribution to life cycle results with a data quality score less than three.
- Low priority – Activities with a low percentage contribution to life cycle results or activities with high data quality scores.

The following is a list of observations from the uncertainty analysis performed.

- The environmental impact with the highest data quality score was climate change. This is in part due to the subprojects that focused on GHG emissions (i.e. FP Innovations and McKechnie) and in part due to the widespread reporting of GHGs worldwide including North America. When empirical emissions data is not available, GHGs can be calculated easily and accurately understanding typical combustion dynamics, mass balances and reaction kinetics.
- For climate change, the highest contributing activities to life cycle results are the biomass recovery, pellet plant, pellet combustion, hog fuel combustion and coal combustion activities. Each of these calculations has a relatively high data quality score of four or higher. Life cycle GHG emissions from this study are also comparable to other published studies which add a layer of confidence to these results. Updating these datasets is low priority.
- On terrestrial acidification (Table 49), the highest contributing activities to life cycle results were the biomass recovery and combustion at the pellet plant and the power plants (biofibre and coal). The data quality for these activities scored above a four with the exception of the biomass harvest and silviculture activities. Also note that the negative values from the slash pile burns are shown as reductions in comparison to the other scenarios. This is because the slash burn amounts are quantified in relation to BH0. In other words, the BH1 scenario (bioenergy scenarios E and F) burn less slash than BH0 and are shown as negative values. The highest priority calculation to update here is the combustion of diesel in forestry field equipment.
- Freshwater eutrophication data quality scores are presented in Table 50. The activities with the highest environmental releases were the coal extraction, pellet pressing and biomass recovery activities. The data quality scores for these activities were relatively low and ranged from 2.25 to 2.75.These low data quality scores are owing to the dependence on Ecoinvent data where the main contributor was the release of phosphates from spoil piles. Unfortunately, phosphate releases were not reported in the lignite mining sub-project or the NPRI data for the Ontario grid where electricity is used to process pellets. It may be that phosphate releases are present in Canada but are below mandatory government reporting thresholds. The reason why there is an absence of phosphate release data in Canada is currently unknown. EC should pursue better data

sources for the major contributing life cycle stages if it considers freshwater eutrophication to be a higher priority environmental impact category.

- Terrestrial ecotoxicity data quality scores are presented in Table 51. The largest contributing activities were pellet combustion, pellet pressing and coal extraction. The data scores for these activities were relatively low and ranged from 2.75 to 3.6. The emission factors for these activities were mainly from Ecoinvent but some NPRI data was available to help proxy the Ontario grid (electricity is used to press pellets). The Ecoinvent pellet combustion process was modified to remove all other subprocesses so that the only processes remaining are directly from pellet combustion. The pellet pressing activity uses grid electricity that results indirectly in ecotoxicity releases. 79% of these releases are cadmium and mercury releases which are proxied using NPRI data (2008 and 2009). The counter-intuitive results of this impact category (pellet combustion having higher terrestrial ecotoxicity releases than coal) makes this process a high priority for future updating.
- Freshwater ecotoxicity data quality scores are presented in Table 52. The largest contributing activities were disposal of coal and wood ash and biomass recovery. Each of these calculations had a relatively low data quality score of 2.75 (or lower). The emission factors for these main activities were from Ecoinvent.
- Land transformation data quality scores are presented in Table 53. The land transformation results are based entirely on Ecoinvent data for all processes. The largest contributing stages are the biomass recovery and the extract coal activities. The relatively low data quality scores, 2.5 and 2.8 for biomass recovery and coal extraction activities respectively, are due to the dependence on Ecoinvent data. Specific harvesting area (data provided by FPInnovations) and coal harvesting area (data provided by the coal subproject) was not included in the land transformation calculations as it is assumed these areas are returned to their natural state. If EC considers land transformation to be an important environmental impact, it is recommended to improve the land transformation results and proxy with localized data.
- The fossil fuel depletion results are similar to land transformation in that they also are driven entirely using Ecoinvent data and data quality scores are shown in Table 54 below. The largest contributing stages are the biomass recovery and the extract coal activities.

Based on these tables, the following conclusions can be made:

- The data quality for the climate change and the terrestrial acidification categories are quite good. The largest contributing stages to life cycle results have data quality scores of 4 or better. The one exception is the acidification emissions from biomass harvest where the data quality score was 2.5. Obtaining acidification emissions for this type of equipment should be easily obtainable.
- The remaining five categories all have relatively poor data quality scores owing to their high dependence on the Ecoinvent database. Many of the Ecoinvent datasets do not score well under this pedigree matrix approach because they are based upon European data (i.e. not geographically representative) or were not published recently (i.e. not temporally representative).

Recommendations:

- Update NH_3, NOx, SO_2 emissions for diesel machinery used in biofibre recovery operations.
- Of all the categories, the most controversial and surprising results are seen in terrestrial ecotoxicity where pellet pathways emit more ecotoxic substances than the coal reference pathway. Since this is an unexpected result that will be met with skepticism, it is important to be confident in the supporting data. It is recommended that empirical pellet combustion data, at the pellet plant and the power plant, be incorporated into the model as soon as it is available. This may be done through a chemical compositional analysis of Canadian biofibre sources or through test burn results. This study derives some data from Envirochem's ongoing work in this area which so far has been to summarize the current state of the biofibre combustion in literature sources. While this is the best information available at the time of this study, it is important to update the results using empirical data when available.
- Further investigate phosphate releases in Canadian mines. The Ecoinvent phosphate releases from spoil piles contribute very significantly to high potential eutrophication impacts for coal.

Table 48. Pedigree scores versus % of life cycle contribution (climate change midpoint)

Life Cycle Stage (climate change)	Emission Factor Source	Activity Data Source	Score	% of life cycle SA	% of life cycle SB	% of life cycle SC	% of life cycle SD	% of life cycle SE	% of life cycle SF	% of life cycle coal
Biomass										
Clear land for forestry roads	FP Innovations	FP Innovations	4.5	0%	0%	0%	0%	0%	0%	
Extract gravel for forestry roads	Ecoinvent	Silvatech	2.5	0%	0%	0%	0%	0%	0%	
Retrofit Atikokan station	Ecoinvent	Econ. alloc.	2.8	3%	2%	0%	0%	4%	0%	
Construct pellet plants	Ecoinvent	n/a	3.3	0%	0%	0%	0%	0%	0%	
Construct cogen plant	Ecoinvent	n/a	3.0	0%	0%	0%	0%	0%	0%	
Aerial spray	FP Innovations	FP Innovations	4.5	2%	1%	0%	0%	1%	6%	
Forest camps	FP Innovations	FP Innovations	4.5	2%	1%	0%	0%	1%	6%	
Recover biomass	FP Innovations	FP Innovations	4.5	58%	39%	8%	4%	38%	47%	
Debark trees	FP Innovations	FP Innovations	4.5							
Chip biomass (wood and slash)	FP Innovations	FP Innovations	4.5							
Transport biomass	FP Innovations	FP Innovations	4.5							
Burn slash piles	SEI	OMNR	4.0	0%	0%	0%	0%	0%	0%	
Pellet plant inventory control	Ecoinvent	McKechnie	3.0	1%	3%	0%	0%	2%	0%	
Debark logs	NIR/NPRI	McKechnie	5.0	0%	0%	0%	0%	0%	0%	
Dry biofibre	Envirochem	McKechnie	4.0	5%	8%	1%	1%	8%	0%	
Press Pellets	NIR/NPRI	McKechnie	5.0	7%	10%	1%	1%	11%	0%	
Transport pellets	Ecoinvent	McKechnie	3.3	4%	5%	1%	1%	5%	0%	
Transport ash (pellet plant)	Ecoinvent	McKechnie	3.3	0%	0%	0%	0%	0%	0%	
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	2.8	0%	0%	0%	0%	0%	0%	
Combust pellets for power	Envirochem	McKechnie	4.0	19%	28%	3%	3%	30%	0%	
Combust hog fuel in cogen	Envirochem	McKechnie	4.0	0%	0%	0%	0%	0%	40%	
Dispose wood ash (power plant)	Ecoinvent	McKechnie	2.8	0%	0%	0%	0%	0%	1%	
Coal										
Construct coal power plant	Ecoinvent	n/a	3.3			0%	0%			1%
Extract coal	Coal SP	McKechnie	5.0			0%	0%			0%
Transport coal to Atikokan	Ecoinvent	McKechnie	3.8			2%	3%			3%
Combust coal	NPRI	McKechnie	5.0			83%	87%			97%
Dispose coal ash	Ecoinvent	McKechnie	2.8			0%	0%			0%

Table 49. Pedigree scores versus % of life cycle contribution (terrestrial acidification midpoint)

Life Cycle Stage (terrestrial acidification)	Emission Factor Source	Activity Data Source	Score	% of life cycle SA	% of life cycle SB	% of life cycle SC	% of life cycle SD	% of life cycle SE	% of life cycle SF	% of life cycle coal
Biomass										
Clear land for forestry roads	Ecoinvent	Silvatech	2.8	0%	0%	0%	0%	0%	0%	
Extract gravel for forestry roads	Ecoinvent	Silvatech	2.5	0%	0%	0%	0%	0%	0%	
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	2.8	1%	1%	0%	0%	2%	0%	
Construct pellet plants	Ecoinvent	n/a	3.3	0%	0%	0%	0%	0%	0%	
Construct cogen plant	Ecoinvent	n/a	3.0	0%	0%	0%	0%	0%	0%	
Aerial spray	Ecoinvent	Assumption	2.0	1%	0%	0%	0%	0%	5%	
Forest camps	Ecoinvent	Assumption	2.5	2%	1%	0%	0%	1%	10%	
Recover biomass	Ecoinvent	Estimated	2.5	18%	9%	4%	2%	24%	43%	
Debark trees	Ecoinvent	Estimated	2.5							
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	3.0							
Transport biomass	Ecoinvent	FP Innovations	3.0							
Burn slash piles	SEI	OMNR	4.0	0%	0%	0%	0%	-76%	-170%	
Pellet plant inventory control	Ecoinvent	McKechnie	3.5	1%	2%	0%	0%	2%	0%	
Debark logs	NPRI	McKechnie	5.0	0%	0%	0%	0%	0%	0%	
Dry biofibre	Envirochem	McKechnie	4.0	19%	22%	5%	5%	35%	0%	
Press Pellets	NPRI	McKechnie	5.0	3%	4%	1%	1%	7%	0%	
Transport pellets	Ecoinvent	McKechnie	3.3	1%	1%	0%	0%	2%	0%	
Transport ash (pellet plant)	Ecoinvent	McKechnie	3.3	0%	0%	0%	0%	0%	0%	
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	2.8	0%	0%	0%	0%	0%	0%	
Combust pellets for power	Envirochem	McKechnie	4.0	52%	59%	12%	13%	103%	0%	
Combust hog fuel in cogen	Envirochem	McKechnie	4.0	0%	0%	0%	0%	0%	210%	
Dispose wood ash (power plant)	Ecoinvent	McKechnie	2.8	0%	0%	0%	0%	0%	1%	
Coal										
Construct coal power plant	Ecoinvent	n/a	3.3			0%	0%			0%
Extract coal	Coal SP	McKechnie	5.0			0%	0%			0%
Transport coal to Atikokan	Ecoinvent	McKechnie	3.8			4%	4%			5%
Combust coal	NPRI	McKechnie	5.0			73%	75%			94%
Dispose coal ash	Ecoinvent	McKechnie	2.8			0%	0%			0%

Table 50. Pedigree scores versus % of life cycle contribution (freshwater eutrophication midpoint)

Life Cycle Stage (freshwater eutrophication)	Emission Factor Source	Activity Data Source	Score	% of life cycle SA	% of life cycle SB	% of life cycle SC	% of life cycle SD	% of life cycle SE	% of life cycle SF	% of life cycle coal
Biomass										
Clear land for forestry roads	Ecoinvent	Silvatech	2.8	0%	0%	0%	0%	0%	0%	
Extract gravel for forestry roads	Ecoinvent	Silvatech	2.5	0%	0%	0%	0%	0%	1%	
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	2.8	15%	8%	0%	0%	12%	0%	
Construct pellet plants	Ecoinvent	n/a	3.3	0%	0%	0%	0%	0%	0%	
Construct cogen plant	Ecoinvent	n/a	3.0	0%	0%	0%	0%	0%	0%	
Aerial spray	Ecoinvent	Assumption	2.0	0%	0%	0%	0%	0%	2%	
Forest camps	Ecoinvent	Assumption	2.5	0%	0%	0%	0%	0%	3%	
Recover biomass	Ecoinvent	Estimated	2.5	17%	13%	0%	0%	16%	66%	
Debark trees	Ecoinvent	Estimated								
Chip biomass (wood and slash)	Ecoinvent	FP Innovations								
Transport biomass	Ecoinvent	FP Innovations								
Burn slash piles	Data gap	Data gap								
Pellet plant inventory control	Ecoinvent	McKechnie	3.5	0%	1%	0%	0%	0%	0%	
Debark logs	Ecoinvent	McKechnie	2.3	0%	2%	0%	0%	0%	0%	
Dry biofibre	Ecoinvent	McKechnie	2.8	10%	11%	0%	0%	9%	0%	
Press Pellets	Ecoinvent	McKechnie	2.3	53%	60%	2%	2%	55%	0%	
Transport pellets	Ecoinvent	McKechnie	3.3	2%	3%	0%	0%	2%	0%	
Transport ash (pellet plant)	Ecoinvent	McKechnie	3.3	0%	0%	0%	0%	0%	0%	
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	2.8	1%	2%	0%	0%	1%	0%	
Combust pellets for power	Ecoinvent	McKechnie	3.0	0%	0%	0%	0%	0%	0%	
Combust hog fuel in cogen	Ecoinvent	McKechnie	3.0	0%	0%	0%	0%	0%	0%	
Dispose wood ash (power plant)	Ecoinvent	McKechnie	2.8	1%	1%	0%	0%	4%	27%	
Coal										
Construct coal power plant	Ecoinvent	n/a	3.3			0%	0%			0%
Extract coal	Ecoinvent	McKechnie	2.8			97%	97%			99%
Transport coal to Atikokan	Ecoinvent	McKechnie	3.8			0%	0%			0%
Combust coal	Ecoinvent	McKechnie	2.8			0%	0%			0%
Dispose coal ash	Ecoinvent	McKechnie	2.8			0%	0%			0%

Table 51. Pedigree scores versus % of life cycle contribution (terrestrial ecotoxicity midpoint)

Life Cycle Stage (terrestrial ecotoxicity)	Emission Factor Source	Activity Data Source	Score	% of life cycle SA	% of life cycle SB	% of life cycle SC	% of life cycle SD	% of life cycle SE	% of life cycle SF	% of life cycle coal
Biomass										
Clear land for forestry roads	Ecoinvent	Silvatech	2.8	0%	0%	0%	0%	0%	0%	
Extract gravel for forestry roads	Ecoinvent	Silvatech	2.5	0%	0%	0%	0%	0%	0%	
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	2.8	1%	1%	1%	0%	1%	0%	
Construct pellet plants	Ecoinvent	n/a	3.3	0%	0%	0%	0%	0%	0%	
Construct cogen plant	Ecoinvent	n/a	3.0	0%	0%	0%	0%	0%	0%	
Aerial spray	Ecoinvent	Assumption	2.0	0%	0%	0%	0%	0%	1%	
Forest camps	Ecoinvent	Assumption	2.5	0%	0%	0%	0%	0%	1%	
Recover biomass	Ecoinvent	Estimated	2.5	11%	8%	8%	6%	7%	10%	
Debark trees	Ecoinvent	Estimated								
Chip biomass (wood and slash)	Ecoinvent	FP Innovations								
Transport biomass	Ecoinvent	FP Innovations								
Burn slash piles	Data gap	Data gap								
Pellet plant inventory control	Ecoinvent	McKechnie	3.5	0%	0%	0%	0%	0%	0%	
Debark logs	NPRI-Ecoinvent	McKechnie	3.6	0%	1%	0%	0%	0%	0%	
Dry biofibre	Ecoinvent	McKechnie	2.8	13%	13%	10%	10%	12%	0%	
Press Pellets	NPRI-Ecoinvent	McKechnie	3.6	19%	20%	15%	15%	20%	0%	
Transport pellets	Ecoinvent	McKechnie	3.3	1%	1%	1%	1%	1%	0%	
Transport ash (pellet plant)	Ecoinvent	McKechnie	3.3	0%	0%	0%	0%	0%	0%	
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	2.8	0%	0%	0%	0%	0%	0%	
Combust pellets for power	Ecoinvent	McKechnie	3.0	54%	55%	41%	42%	58%	0%	
Combust hog fuel in cogen	Ecoinvent	McKechnie	3.0	0%	0%	0%	0%	0%	88%	
Dispose wood ash (power plant)	Ecoinvent	McKechnie	2.8	0%	0%	0%	0%	0%	0%	
Coal										
Construct coal power plant	Ecoinvent	n/a	3.3			0%	0%			4%
Extract coal	Ecoinvent	McKechnie	2.8			14%	14%			56%
Transport coal to Atikokan	Ecoinvent	McKechnie	3.8			3%	3%			12%
Combust coal	NPRI-Ecoinvent	McKechnie	3.9			5%	6%			23%
Dispose coal ash	Ecoinvent	McKechnie	2.8			1%	1%			5%

Table 52. Pedigree scores versus % of life cycle contribution (freshwater ecotoxicity midpoint)

Life Cycle Stage (freshwater ecotoxicity)	Emission Factor Source	Activity Data Source	Score	% of life cycle SA	% of life cycle SB	% of life cycle SC	% of life cycle SD	% of life cycle SE	% of life cycle SF	% of life cycle coal
Biomass										
Clear land for forestry roads	Ecoinvent	Silvatech	2.8	1%	1%	0%	0%	0%	0%	
Extract gravel for forestry roads	Ecoinvent	Silvatech	2.5	0%	0%	0%	0%	0%	0%	
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	2.8	3%	2%	1%	0%	2%	0%	
Construct pellet plants	Ecoinvent	n/a	3.3	0%	0%	0%	0%	0%	0%	
Construct cogen plant	Ecoinvent	n/a	3.0	0%	0%	0%	0%	0%	0%	
Aerial spray	Ecoinvent	Assumption	2.0	2%	1%	1%	0%	0%	2%	
Forest camps	Ecoinvent	Assumption	2.5	2%	1%	1%	0%	0%	2%	
Recover biomass	Ecoinvent	Estimated	2.5	44%	28%	11%	7%	23%	20%	
Debark trees	Ecoinvent	Estimated	2.5							
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	3.0							
Transport biomass	Ecoinvent	FP Innovations	3.0							
Burn slash piles	Data gap	Data gap								
Pellet plant inventory control	Ecoinvent	McKechnie	3.5	1%	3%	0%	1%	1%	0%	
Debark logs	Ecoinvent-NPRI	McKechnie	3.6	0%	0%	0%	0%	0%	0%	
Dry biofibre	Ecoinvent	McKechnie	2.8	3%	3%	1%	1%	2%	0%	
Press Pellets	Ecoinvent-NPRI	McKechnie	3.6	10%	11%	3%	3%	7%	0%	
Transport pellets	Ecoinvent	McKechnie	3.3	5%	5%	1%	1%	3%	0%	
Transport ash (pellet plant)	Ecoinvent	McKechnie	3.3	0%	0%	0%	0%	0%	0%	
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	2.8	10%	26%	2%	6%	8%	0%	
Combust pellets for power	Ecoinvent	McKechnie	3.0	6%	6%	1%	1%	4%	0%	
Combust hog fuel in cogen	Ecoinvent	McKechnie	3.0	0%	0%	0%	0%	0%	4%	
Dispose wood ash (power plant)	Ecoinvent	McKechnie	2.8	14%	14%	3%	3%	48%	70%	
Coal										
Construct coal power plant	Ecoinvent	n/a	3.3			0%	0%			1%
Extract coal	Ecoinvent	McKechnie	2.8			22%	22%			28%
Transport coal to Atikokan	Ecoinvent	McKechnie	3.8			5%	5%			6%
Combust coal	Ecoinvent-NPRI	McKechnie	3.9			1%	1%			1%
Dispose coal ash	Ecoinvent	McKechnie	2.8			48%	49%			64%

Table 53. Pedigree scores versus % of life cycle contribution (land transformation midpoint)

Life Cycle Stage (land transformation)	Emission Factor Source	Activity Data Source	Score	% of life cycle SA	% of life cycle SB	% of life cycle SC	% of life cycle SD	% of life cycle SE	% of life cycle SF	% of life cycle coal
Biomass										
Clear land for forestry roads	Ecoinvent	Silvatech	2.8	1%	1%	0%	0%	0%	0%	
Extract gravel for forestry roads	Ecoinvent	Silvatech	2.5	0%	0%	0%	0%	1%	3%	
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	2.8	7%	5%	2%	1%	7%	0%	
Construct pellet plants	Ecoinvent	n/a	3.3	0%	0%	0%	0%	0%	0%	
Construct cogen plant	Ecoinvent	n/a	3.0	0%	0%	0%	0%	0%	1%	
Aerial spray	Ecoinvent	Assumption	2.0	4%	4%	1%	1%	2%	13%	
Forest camps	Ecoinvent	Assumption	2.5	4%	4%	1%	1%	1%	13%	
Recover biomass	Ecoinvent	Estimated	2.5	67%	55%	22%	13%	68%	75%	
Debark trees	Ecoinvent	Estimated	2.5							
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	3.0							
Transport biomass	Ecoinvent	FP Innovations	3.0							
Burn slash piles	Data gap	Data gap								
Pellet plant inventory control	Ecoinvent	McKechnie	3.5	3%	9%	1%	2%	4%	0%	
Debark logs	Ecoinvent	McKechnie	2.3	0%	0%	0%	0%	0%	0%	
Dry biofibre	Ecoinvent	McKechnie	2.8	3%	5%	1%	1%	4%	0%	
Press Pellets	Ecoinvent	McKechnie	2.3	5%	8%	2%	2%	7%	0%	
Transport pellets	Ecoinvent	McKechnie	3.3	6%	10%	2%	2%	9%	0%	
Transport ash (pellet plant)	Ecoinvent	McKechnie	3.3	0%	0%	0%	0%	0%	0%	
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	2.8	0%	-1%	0%	0%	-1%	0%	
Combust pellets for power	Ecoinvent	McKechnie	3.0	0%	0%	0%	0%	0%	0%	
Combust hog fuel in cogen	Ecoinvent	McKechnie	3.0	0%	0%	0%	0%	0%	0%	
Dispose wood ash (power plant)	Ecoinvent	McKechnie	2.8	0%	-1%	0%	0%	-3%	-5%	
Coal										
Construct coal power plant	Ecoinvent	n/a	3.3			0%	0%			2%
Extract coal	Ecoinvent	McKechnie	2.8			57%	65%			92%
Transport coal to Atikokan	Ecoinvent	McKechnie	3.8			13%	15%			8%
Combust coal	Ecoinvent	McKechnie	2.8			1%	1%			0%
Dispose coal ash	Ecoinvent	McKechnie	2.8			-4%	-4%			-2%

Table 54. Pedigree scores versus % of life cycle contribution (fossil fuel depletion midpoint)

Life Cycle Stage (fossil fuel depletion)	Emission Factor Source	Activity Data Source	Score	% of life cycle SA	% of life cycle SB	% of life cycle SC	% of life cycle SD	% of life cycle SE	% of life cycle SF	% of life cycle coal
Biomass										
Clear land for forestry roads	Ecoinvent	Silvatech	2.8	1%	1%	0%	0%	0%	0%	
Extract gravel for forestry roads	Ecoinvent	Silvatech	2.5	0%	0%	0%	0%	0%	0%	
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	2.8	5%	4%	1%	0%	5%	0%	
Construct pellet plants	Ecoinvent	n/a	3.3	0%	0%	0%	0%	0%	0%	
Construct cogen plant	Ecoinvent	n/a	3.0	0%	0%	0%	0%	0%	0%	
Aerial spray	Ecoinvent	Assumption	2.0	3%	3%	1%	0%	1%	10%	
Forest camps	Ecoinvent	Assumption	2.5	3%	3%	1%	0%	1%	10%	
Recover biomass	Ecoinvent	Estimated	2.5	64%	52%	11%	6%	63%	78%	
Debark trees	Ecoinvent	Estimated	2.5							
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	3.0							
Transport biomass	Ecoinvent	FP Innovations	3.0							
Burn slash piles	Data gap	Data gap								
Pellet plant inventory control	Ecoinvent	McKechnie	3.5	2%	6%	0%	1%	3%	0%	
Debark logs	Ecoinvent	McKechnie	2.3	0%	0%	0%	0%	0%	0%	
Dry biofibre	Ecoinvent	McKechnie	2.8	3%	4%	0%	1%	3%	0%	
Press Pellets	Ecoinvent	McKechnie	2.3	11%	15%	2%	2%	13%	0%	
Transport pellets	Ecoinvent	McKechnie	3.3	7%	11%	1%	1%	9%	0%	
Transport ash (pellet plant)	Ecoinvent	McKechnie	3.3	0%	0%	0%	0%	0%	0%	
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	2.8	0%	0%	0%	0%	0%	0%	
Combust pellets for power	Ecoinvent	McKechnie	3.0	0%	0%	0%	0%	0%	0%	
Combust hog fuel in cogen	Ecoinvent	McKechnie	3.0	0%	0%	0%	0%	0%	0%	
Dispose wood ash (power plant)	Ecoinvent	McKechnie	2.8	0%	0%	0%	0%	0%	1%	
Coal										
Construct coal power plant	Ecoinvent	n/a	3.3			0%	0%			1%
Extract coal	Ecoinvent	McKechnie	2.8			78%	82%			92%
Transport coal to Atikokan	Ecoinvent	McKechnie	3.8			5%	5%			6%
Combust coal	Ecoinvent	McKechnie	2.8			0%	0%			0%
Dispose coal ash	Ecoinvent	McKechnie	2.8			0%	0%			0%

Finally, Table 55 summarizes the data sources for the forest carbon and landscape-level components. As shown in this table, the overall score for these data sources is relatively high compared to the Ecoinvent components. Only the GIS shape files received a score less than three. It is recommended to update the GIS shape files specific to the FMUs in this study.

Table 55. Pedigree scores for forest carbon and landscape-level work

Activity	Activity Data Source	Temporal Representation (1-5)	Geographical Representation (1-5)	Activity Data Certainty (1-5)	Score
GIS shape files	OMNR	2	5	3	3.3
Growth and Yield Curves	OMNR	4	5	4	4.3
Natural Disturbance	OMNR	4	5	4	4.3
Forest harvest rates	FPInnovations	4	4	4	4.0
In-block slash	FPInnovations	4	4	4	4.0
Road construction	FPInnovations	4	4	4	4.0

6.2 Sensitivity analysis

6.2.1 Allocation of potential environmental impacts to forestry slash

Waste products from industrial processes are often referred to as “free” products without any upstream environmental impacts connected with it because the product is perceived to have no value. The problem is that once a use for that product is identified, the waste now inherently has an economic or social value and should no longer be considered a waste product. Forestry slash is a prime example since aside of being used as a feedstock it will decay at roadside or be burned at roadside. This project aims to model forestry slash as a feedstock for brown pellets or hog fuel and this sensitivity case tests to see how much of a potential environmental impact there is when the slash is considered a useful product.

There are environmental impacts from the harvest, skidding and processing of the tree. Recall that in a multi-product process, emissions are assigned to the different product streams through an LCA process called allocation. Allocation can be done on a mass, energy or economic value basis. The allocation to slash in this sensitivity case is performed using a mass ratio of 34% meaning that 34% of the mass of the tree ends up as slash. The sensitivity is performed on Scenario E.

The allocation is applied to all activities upstream of where the slash occurs at roadside. This includes the forest recovery, silviculture and forest road construction and maintenance. Activities to chip slash, transport biofibre and pelletize are not allocated because they are downstream processes of the slash.

The effect of allocating potential environmental impacts to slash is shown in Figure 61 below.

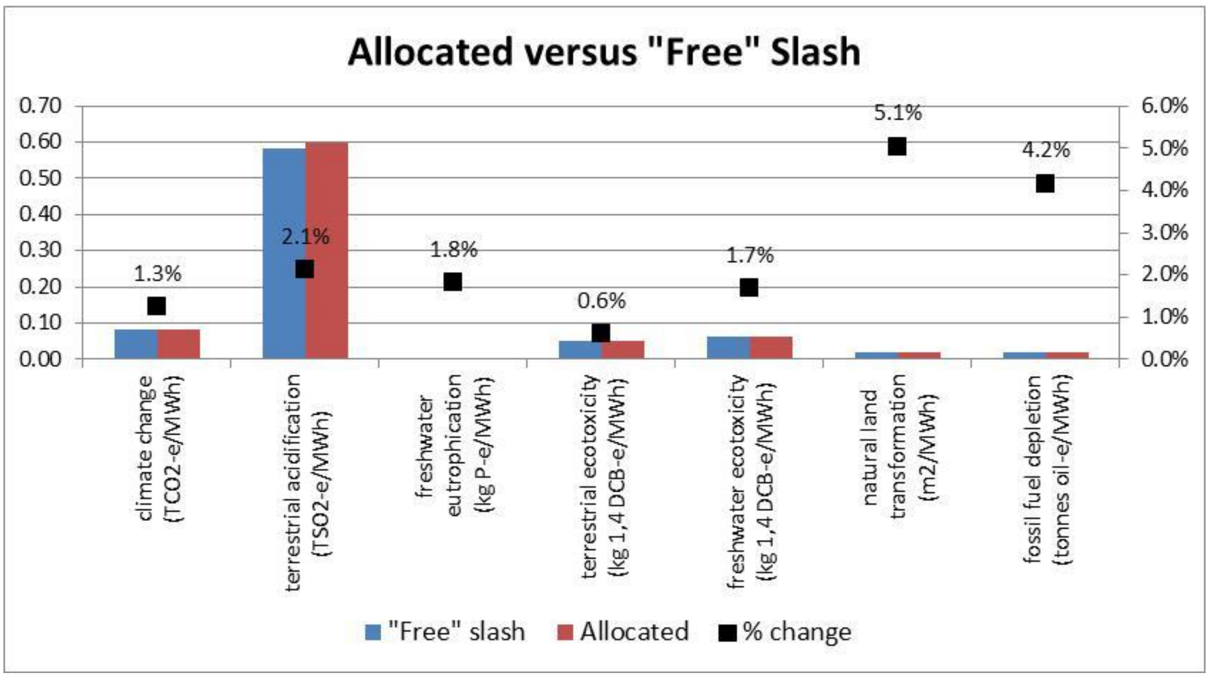


Figure 61. Allocated versus “free” slash potential environmental impacts (Scenario E)

The graph shows that the life cycle results for each of the seven impact categories are not significantly affected.

6.2.2 Allocation for CHP

CHP plants are a common multi-output process because they produce two products in heat and electricity. The CHP plant is modelled in the main body of the report as a “modified CHP” plant as described in Section 3.3.6 where the heat output is equivalent to a theoretical electricity benefit. The overall electrical efficiency of the CHP is 35.1% and is the sum of the actual electricity generated plus the theoretical electricity benefit (from heat). This methodology was put forth by the Advisory Committee in the early stages of the project.

The more conventional LCA approach to a multi-output process like CHP is to allocate environmental burdens using a mass balance, energy balance or economic value basis. This sensitivity uses an energy balance to divide the environmental burdens between the product streams. An allocation factor of 33% is calculated using a ratio of the heat and electricity output ratios (i.e. there are three GJ of heat produced for every GJ of electricity produced). Each life cycle process is multiplied by this ratio when allocating environmental burdens. 33% of the environmental burdens through the life cycle are allocated to the electricity production and 67% to the heat production. When results are tallied, they are only counted for the electricity portion. The consumer of the heat product is responsible for the heat (or 67%) of the environmental burdens.

Figure 62 below shows life cycle results when using the "modified cogen" and the allocated cogen cases. Allocating environmental releases to cogen power results in lower environmental releases compared with the modified cogen approach.

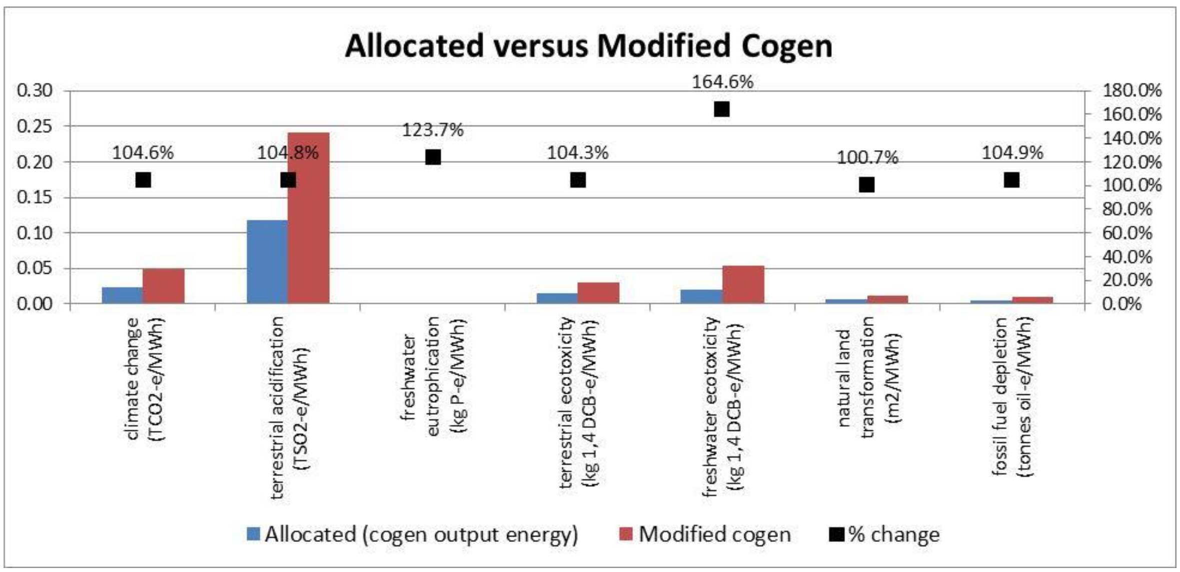


Figure 62. Allocated versus modified cogen environmental impacts (Scenario F)

It can be seen from the chart that the allocated cogen case appears to have fewer environmental impacts than the "modified cogen" case.

6.2.3 NREL biofibre combustion emission factors

The bioenergy scenarios have produced some counter-intuitive results for the terrestrial ecotoxicity impact category and much of the concern is from the biofibre combustion emission factors used in the study (recall that environmental releases are modelled using a combination of Envirochem and Ecoinvent emission factors). This sensitivity case uses NREL combustion emission factors in substitution of the Envirochem-Ecoinvent data that has been used in the main body of the report.

The NREL dataset used for this sensitivity test was "Wood fuel, NE-NC hardwood, purchased, combusted in industrial boiler". This dataset had emission factors for acetyldehyde, acrolein, antimony, arsenic, benzene, beryllium, cadmium, chlorine, chromium, cobalt, dioxins, formaldehyde, lead, manganese, mercury, methane, nickel, NOx, Sox and selenium. Each of these values was used and all other terrestrial and freshwater ecotoxicity factors were removed.

The specific emission factors were "proxied" and continue to use ReCiPe characterization factors.

Figure 63 compares the life cycle results using NREL emission factors versus the Envirochem-Ecoinvent factors used in the main body of this report.

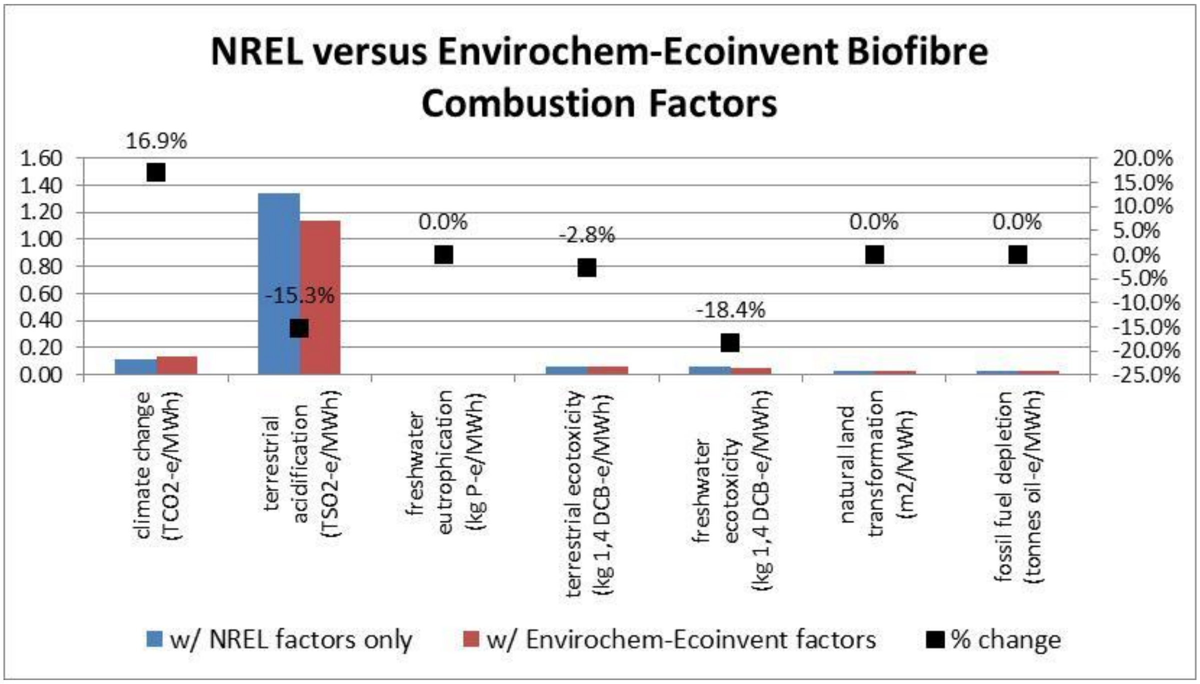


Figure 63. NREL versus Envirochem-Ecoinvent biofibre combustion factors (Scenario A)

The results show that the NREL set of emission factors for biofibre combustion are in-line with what is used in this study (combination of Envirochem and Ecoinvent). Table 56 below shows a comparison with the coal life cycle results. The life cycle terrestrial ecotoxicity releases from biofibre are higher than coal regardless of which set of emission factors is used.

Table 56. Life cycle results for NREL versus Envirochem-Ecoinvent sensitivity

	w/ NREL factors only	w/ Envirochem-Ecoinvent factors	Coal
climate change (TCO2-e/MWh)	0.113	0.132	1.253
terrestrial acidification (TSO2-e/MWh)	1.341	1.136	6.456
freshwater eutrophication (kg P-e/MWh)	0.005	0.005	0.178
terrestrial ecotoxicity (kg 1,4 DCB-e/MWh)	0.059	0.057	0.015
freshwater ecotoxicity (kg 1,4 DCB-e/MWh)	0.061	0.050	0.242
natural land transformation (m2/MWh)	0.030	0.030	0.193
fossil fuel depletion	0.026	0.026	0.190

(tonnes oil-e/MWh)			

6.2.4 Decay rate of roadside slash – BH1

A sensitivity was performed on the decay rate defined for the roadside slash since the roadside slash was modelled to decay differently compared to in-block slash. Data was limited on the decay rates and behavior of roadside slash and for the carbon modelling performed, the 25th percentile of reported range of decay parameters were used. The sensitivity was also extended beyond the 100-year planning horizon to test whether the forest carbon changes for BH1 would approach steady state.

Figure 64 shows that roadside decay rates have an impact on the change in the rate and amount of total forest carbon. As the decay rate is increased, carbon loss reaches a steady state quicker and amount of forest carbon loss decreases. To determine the impacts different decay rates might have on overall forest carbon for BH1, more analysis is required.

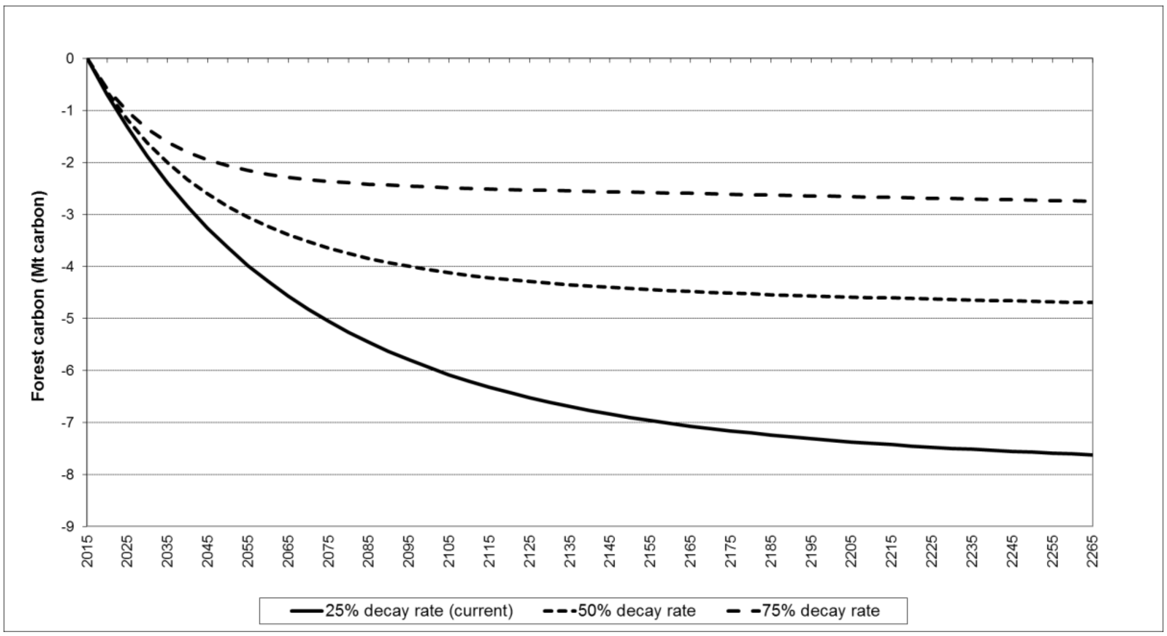


Figure 64. Sensitivity analysis – Decay rate of roadside slash

7. Summary of key findings, discussion and next steps

The following section summarizes the key findings from the life cycle inventory, analysis and interpretation of the results.

7.1 Key findings and observations

7.1.1 Forest carbon

The impacts to forest carbon varying depending on the biofibre resource utilized and the continuous harvest of annual biofibre volumes required for BH1, BH2 and BH3. All discussion points are relative to the BH0 baseline.

<u>Roadside slash utilization</u>

- Utilizing available roadside slash for either brown pellets or hog fuel has the smallest carbon impact of the three bioharvest scenarios. Throughout the planning horizon for BH1, there is a small, but continuous decrease in forest carbon stocks where the landbase is a source of carbon. This decrease is most significant early on in the planning horizon and levels off throughout the 100 years.
- A contributing factor to the relatively small (compared to BH2 and BH3, discussed next) decrease in carbon stocks for BH1 is the fact that approximately 32% of the roadside slash is burned in the BH0 baseline. The remaining roadside slash that is left in BH0 will decay and thus also contribute to the decrease in carbon stocks.
- In the short-term (10 years) there is a decrease of -1.3 Mt carbon; in the mid-term (50 years) there is a decrease of -4.3 Mt carbon and in the long term there is a decrease of -6.3 Mt carbon.

<u>Full-tree harvesting</u>

- Harvesting and utilizing standing hardwood trees for white pellets has significant carbon impacts for BH2 and BH3 – much more than BH1.
- For BH2, where the percent utilization of the AAC is increased from approximately 45% to 75%, there is an immediate and continuous decrease in forest carbon stocks for the first 75 years where the landbase is a source of carbon. After 75 years, the landbase acquires more carbon than is being lost by continual harvesting and the landbase being a sink of carbon.

- For BH2, in the short-term (10 years) there is a decrease of -4.6 Mt carbon; in the mid-term (50 years) there is a decrease of -16.0 Mt carbon and in the long term there is a decrease of -15.9 Mt carbon. This decrease in carbon is a combination of the carbon contained in the biofibre being harvested, the further carbon loss as a result of the decay of DWD and the fact that the trees harvested would continue to grow in the baseline scenario.
- For BH3, where the percent utilization of the AAC is increased from approximately 45% to 95%, there is also an immediate and larger continuous decrease in forest carbon stocks for the first 65 years where the landbase is a source of carbon. After 65 years, the landbase acquires more carbon than is being lost by continual harvesting and the landbase being a sink of carbon. The landbase becomes a carbon sink sooner in BH3 and BH2 because the process used to define the BH3 utilization rates for all forest units and carbon is a function on the specific forest unit harvested and age of the stand at the time of harvest. The earlier inflection point is more of a symptom of modelling parameters and the forest units defined for harvesting.
- For BH3, in the short-term (10 years) there is a decrease of -9.1 Mt carbon; in the mid-term (50 years) there is a decrease of -30.2 Mt carbon and in the long term there is a decrease of -28.5 Mt carbon. This decrease in carbon is a combination of the carbon contained in the biofibre being harvested, the further carbon loss as a result of the decay of DWD and the fact that the trees harvested would continue to grow in the baseline scenario.

7.1.2 Life cycle GHG emissions

The life cycle GHG emissions from the all upstream and downstream activities were quantified using the ReCiPe and ecoInvent data, localized with GHG emission data where possible. Upstream and downstream activities for the coal reference case (and coal portions in the co-firing scenarios) include commissioning, extraction, processing, transportation, power plant and ash management activities. Upstream and downstream activities for the bioenergy reference cases include commissioning, harvesting, comminution, silviculture, transportation, pellet plant, power plant and ash management. All GHG emission intensities are normalized to the LCA's functional unit which is 1 MWh and do not include biogenic carbon emissions from bioenergy combustion.

- The GHG emission intensity for coal is 1,253 kg CO2e / MWh. For the coal reference case, the largest percentage of the GHG emissions is from the combustion of coal.
- The GHG emissions intensities for all bioenergy scenarios are less than coal, with bioenergy scenarios E and F having the largest decrease from coal – approximately 95%.
- For bioenergy scenarios A and B (full-tree harvesting and 100% pellets), the largest percentage of GHG emissions comes from bioharvest recovery (harvesting, comminution, transportation).
- For bioenergy scenarios C and D (full-tree harvesting and co-firing), the largest percentage of GHG emissions comes from coal combustion.

- For bioenergy scenarios E and F (slash), the largest percentage of GHG emissions comes from bioharvest recovery.
- The GHG emissions modelled and provided by FPInnovations which included harvesting, comminution, silviculture and transportation were 10% higher for BH1, 90% higher for BH2 and 50% higher for BH3 compared to the results using the Ecoinvent database. Since the FPInnovations BiOS modelling is quite specific and detailed specific to the site conditions, the FPInnovations results are considered to be more accurate.
- The overall GHG emission results using the Ecoinvent and ReCiPe framework are in-line with other published LCA biomass studies.

However, when forest carbon component is added to the life cycle GHG emissions, the overall GHG emission intensities for the bioenergy scenarios are not as favorable because of the carbon impacts from sourcing and utilizing the biofibre from the landbase.

- The GHG emission intensities for bioenergy scenario E and F are 76% below coal and offer the greatest GHG emission reduction when utilizing this slash resource.
- The GHG emission intensities for bioenergy scenario A, B, C and D vary slightly, but on average, are approximately 5% below coal, depending on the bioharvest scenario and co-firing. There is not a significant GHG emission reduction when utilizing standing trees.

7.1.3 Terrestrial Acidification

- There is a decrease in the terrestrial acidification potential when replacing coal with any of the biofibre pathways. This is mainly due to the high SO_2 emissions from coal combustion at power plant.
- There is a marginal decrease in SO_2e emissions when biofibre is extracted as logs from the forest and chipped at a pellet facility, as diesel fuel is being replaced with Ontario grid electricity.
- There is further reduction in SO2e emissions from using roadside slash as opposed to tree harvesting. This is due in part to the reduced diesel combustion in forestry machinery.

7.1.4 Freshwater Eutrophication

- There is a decrease in freshwater eutrophication environmental releases when replacing coal with any of the biofibre pathways.
- The main contributor to this result is phosphate releases to ground water at lignite mine.
- Environmental release information on phosphates is obtained through Ecoinvent. It is not clear at this time whether phosphate releases to ground water is occurring in Canada. Three Canadian mines were examined in Western Canada and none reported any phosphate releases in their documentation.

7.1.5 Terrestrial ecotoxicity

- All six biofibre fuel pathways contribute more to terrestrial ecotoxicity than the coal reference pathway. This result is driven by the need to use Ecoinvent emission factors for biofibre combustion as there is no local data specific to the pellets or pellet combustion technologies.

7.1.6 Freshwater ecotoxicity

- There is a decrease in freshwater ecotoxicity releases when fuel switching from the coal reference scenario to any of the six biofibre scenarios.
- The main contributing factor is the high freshwater ecotoxic releases of coal ash disposal in landfill.

7.1.7 Natural land transformation

For all bioenergy scenarios, there is a general decrease in natural land transformation compared to coal.

- The primary reason for the reduction in natural land transformation is XXX.

7.1.7.1 Fossil fuel depletion

For all the bioenergy scenarios, there is a decrease in the fossil fuel depletion compared to coal.

- The primary reason for the reduction in fossil fuel is due to the reduced coal consumption when fuel switching to any of the six bioenergy scenarios.
- There is also a reduction of fossil fuel in fuel procurement in the transportation distances of coal from Western Canada.

7.1.8 Seral stage and CWD (structure)

This study forecasts and measures forest structure in two ways; seral class distribution and CWD. The following points summarize the key findings from these two metrics.

- There are significant differences in seral stage and CWD metrics across the bioenergy scenarios – with the exception of old forest, which is largely insensitive to BH2 and BH3.
- All bioharvest scenarios reduce the amount of old and mature forest. Compared with current BH0 harvest levels, the BH2 scenario brings an 80 % reduction in mid to early-old forest within 50 years. The BH3 scenario reaches this state in just over 30 years.
- All scenarios increase the prevalence of early seral stands. BH3 results in the greatest increase - 61% relative to BH0.
- Elements of biodiversity with a preference or perhaps obligation for early seral stands will have increased opportunities in the long term and this is not likely to change beyond 100 years. Given the relatively long natural disturbance cycles for these ecosystems, this increased predominance of early seral stands may well be outside the bounds of the range of natural variance.

- The accumulation component of CWD declines rapidly and extensively. Relative to BH0, accumulation CWD is reduced in BH2 by 78% and in BH3 by 89 % withinin 50 years. The change is persistent through the planning horizon with BH2 reduced by 92% in 100 years and BH3 by 96%.
- Elements of biodiversity dependant on older forest with complex structure and high amounts of accumulation CWD will have significantly fewer opportunities. There may also be significant implications for nutrient cycling in the long term particularly for the BH3 scenario as the regenerating watersheds see a significant and sustained change in ground level CWD.

In the prairie surface coal mine comparison, the qualitative assessment looks at the change in microsite, dominant vegetation and landform.

- Biodiversity is expected to be reduced. The localized microsite complexity created by mine spoil dumping has created suitable habitat for a number of species of wildlife and flora that currently occupy the site. However, the site will be completely transformed to a forage / crop mix of vegetation on a gently undulating land form but no quantitative measure is available.
- The transformation from a highly irregular microsite dominated by a range of vegetation including shrubs and trees to a gently undulating agricultural landscape is a significant alteration of the structural attributes of the area.

7.1.8.1 Fragmentation

In all the biomass harvesting scenarios, linear networks of roads, edge associated with harvest areas and burns all contribute to increased fragmentation.

- Relative to BH0, the BH2 and BH3 scenarios result in significant and steady increases in landscape fragmentation. In BH3, fragmentation is 69% higher than current practice within 50 years and continues to increase to 134% by year 100.
- The rate of increase is not expected to be sustained indefinitely but the increased amount of fragmentation is.
- The landscape change is expected to be persistent which deviates substantially from what would be expected within the bounds of RNV.
- Fragmentation is an important factor for biodiversity in prairie landscapes. Edge increases the potential for traffic related collisions, acts as a vector for invasive species introduction, disrupts natural drainage patterns, creates stream discontinuity, interrupts the movement of animals and plants, can reduce the potential for gene pool movement and interaction and habitat quality can be degraded due to avoidance or the effects of light and noise.

The region is heavily fragmented by agriculture with a current linear edge density of approximately 2.4 km/km2 and the incremental additions from this mine site will be negligible.

7.2 Recommendations for next steps

The following section summarizes the key recommendations for next steps based on the results and observations made. Recommendations are also provide to help facilitate successful evolution of this LCA model in future work.

7.2.1 Project Scope

- **Annual electricity generated for each bioenergy scenario** – Define an annual fixed and equivalent annual electricity generation for each bioenergy scenario. By defining an annual fixed electricity generation, specific and different annual biofibre requirements can be defined for each bioenergy scenario. This will provide more realistic scenario development and facilitate more advanced modelling for biofibre availability, carbon modelling and landscape-level modelling. Having the capability of defining different annual biofibre requirements will enable more precise comparison between 100% biofibre utilization and co-firing where the amount of biofibre would change according to the co-firing rate.
- **Coal reference case** – The data collected for the coal reference case was generic to open-pit coal mining in Western Canada. It is recommended to further increase the certainty of the data for the coal reference case by obtaining data specific to the Bienfait mine in Saskatchewan.
- **Natural gas reference case –** Include a natural gas reference case in the analysis. Including a natural gas reference case will aid in further decision making regarding bioenergy being a replacement fuel for fossil fuels.
- **Comprehensive spatial analysis** – To improve on the 100-year forecasting method (which for this project used 5- and 10-year FMP data), perform a comprehensive spatial fibre supply analysis to forecast all cut block and harvest levels throughout the entire planning horizon. This would include a forest of the precise kilometers of road by class needed for construction, maintenance, rebuild and rehabilitation.
- **Forest carbon accounting frameworks** – Since forest carbon significantly impacts the overall GHG emission results, research different forest-based carbon accounting methodologies to better understand the “state-of-the-debate”.
- **Further integration of traditional and nontraditional impacts** – Linking non-traditional environmental indicators to full life cycle impacts and expressing these as functional unit is challenging. Develop a methodology that further integrates these non-traditional indicators so overall decisions can be made regarding the importance of these indicators.

7.2.2 Biofibre availability data

- **Optimize biofibre harvesting** – Optimize the planning of stand targeting to understand the impact various harvest plans have on forest carbon results. There is potential to target different stands that may result in a smaller carbon compared to other stands.

- **Variable annual harvest area** – Constant annual harvest areas (6,111 ha for BH2; 11,899 ha for BH3) were utilized to calculate annual biofibre availability. Consider integrating the variable harvest areas modelled through the landscape-level subproject to more accurately model the changing area based on seral class and stand targets.

7.2.3 LCA modelling framework and boundary

- **Expand to a boundary of the LCA analysis** – Consider expanding to a basin-wide analysis, instead of the just 4 FMU landbase.
- **CHP Allocation method –** The current ISO method used for the CHP plant in bioenergy scenario F is using allocation method instead of system expansion. Allocation was selected because of the lack of a natural gas pathway. ISO guidelines prefer system expansion and recommends allocation as a last resort. It is recommended to include a natural gas pathway in future work and incorporate system expansion for bioenergy scenario F and the rest of the bioenergy scenarios.
- **Silviculture activities** – Activity and production data on upstream activities associated with softwood seedling production – seed production, greenhouse operation, fertilizer production and use was extremely limited. Silviculture data was focused and specific to GHGs emissions. Special consideration should be given to the application of glyphosate and the contribution of this activity to potential environmental impacts.
- **Temporal inclusion for land-use** – The natural land transformation midpoint in this work is time independent. It is recommended to evolve to include land occupation in the ReCiPe framework which is time dependent. This will provide a better sense of the temporal aspects of land change. This is especially important considering coal and biofibre extraction and reclamation.
- **Uncertainty Assessment** – Investigate statistical methods, such as a Monte Carlos method to further calculate uncertainty of the results.
- **Forestry roads** – Accurately model main forestry roads and tertiary roads by including construction, maintenance, rebuild and rehabilitation activities.

7.2.4 Additional environmental impacts

- **Include human health endpoint from ReCiPe framework** – Currently, all selected midpoints converge to the *ecosystem quality* endpoint, which is an indicator of biodiversity. Consideration should be given to the human health endpoint which is considered a valuable endpoint within the ReCiPe framework.
- **Include particulate matter (PM) midpoint** – Include the PM midpoint in the ReCiPe framework, especially considering the inclusion of open slash pile burning in the BH0 baseline scenario.
- **Soil productivity / nutrient cycling** – Data / research in this area is still evolving. Consider and support further research in this area to hopefully better understand the effects of biofibre harvest on soil productivity and nutrient cycling specific to this case study.

- **Water hydrological model -** Incorporate a detailed hydrologic model that tracks water and nutrient flows through the landbase.
- **Community-level impacts –** With the completion of the landscape-level analysis, a better understanding of the implications for specific values would be well served by a community-level assessment of the forecasted landbase changes. In addition, this approach would enable an assessment of this in more multi-land use areas, accommodate a large range of natural disturbance regimes and could assess the implications of climate change.

7.2.5 Ecoinvent modelling

- **Investigate key Ecoinvent processes –** There are a few critical Ecoinvent processes that did not suitably match the activities included in the LCA boundary. These processes include *Burn slash at roadside (BR8), Transport biofibre to pellet plant (BR7), Dry biofibre (PeP3a), Combust pellets in boiler (PoP4a)*. It is recommended to conduct further research to more accurately model these key processes.
- **Research pellet combustion emission factors** – Obtain actual pellet combustion burn data, or perform a chemical composition analysis and proxy this information in the modelling. Differentiation between brown and white pellets emission factors should be made.
- **Co-fire scenarios – NOx / SOx interaction** – Ecoinvent does not have the capabilities to model the complicated chemical interaction of co-firing biomass with coal – specifically SOx and NOx emissions. The combustion of coal and pellets processes in the co-fire scenarios processes are currently modelled independently in Ecoinvent.
- **Further investigate phosphate releases in Canadian coal mines –** To more accurately model the potential eutrophication environmental impacts, research and proxy phosphate releases from spoil piles.
- **Canadian characterization factors** – Research is currently being completed by IMPACT 2002+ to develop Canadian-specific midpoint characterization factors for Ecoinvent. Once published, it is recommended to integrate these Canadian characterization factors into the LCA model.
- **FPInnovations GHG emission results** – Further investigate the variance in the FPInnovations GHG emission results and Ecoinvent GHG emission results to determine if scaling of other environmental impacts is warranted.

7.2.6 Landscape-level modelling

- **Forestry road network inventories –**The GIS data provided has been compiled using Planning Composite Inventory (PCI) data rather than the Forest Resource Inventory (FRI). As a result, the current active road inventory is not fully represented in the data used. It is recommended to update the forestry road network inventories.

Appendix A. Details of biofibre harvesting

This information is taken from the FPInnovations report.

Biofibre harvesting scenarios

Each of the SFL's needs to produce a 10-year plan of the harvest level and the location of the cut blocks for the period. Although the forest management plans are for a 10 year period, similar harvesting levels are assumed throughout the full rotation period, as the 10 year plans are developed to ensure the sustainability of the forest resource. Therefore, our results represent a good estimate of future feedstock availability as well. The management plans will be used as the basis for predicting biomass availability for 3 Biofibre harvesting scenarios (BH1 to BH3) using recent historical level of harvest as the current "business as usual" harvest level (BH0):

BH0 (existing practice)

- Current harvesting practices in Northwestern Ontario.
- Continuation of recent historical harvest rates.
- Conifer-dominated stands are targeted as priority (weak market for hardwood); hardwood-dominated stand are only targeted if demand for hardwood products justify it;
- At least 25 trees/ha are left standing for biodiversity purposes (including unmarketable trees).
- Harvesting method is predominantly full-tree-to-roadside (conventional or DDC systems); cut-to-length is only used on sites with shallow or sensitive soils.
- Approximately 50% of the slash is left on cut-blocks and 50% is piled at roadside for full-tree harvesting systems; 100% for cut-to-length systems.
- Road-side slash management is often limited to slash piling to avoid losing growing area; roadside pile burning is also used in some SFL (see slash management section)
- Road-side slash recovery has been initiated in some of the SFL but still at low annual volumes (considered as not significant for this analysis).

BH1 (residues recovery)

- Continuation of historical harvest rates.
- Roadside residues recovery (slash only) from current harvesting practices (BH0) in currently planned harvesting operations (no additional harvest for biofibre).
- Average recovery rate of roadside residues of 75%.
- No residues recovery from cut-to-length systems.

BH2 (increased hardwood harvest)

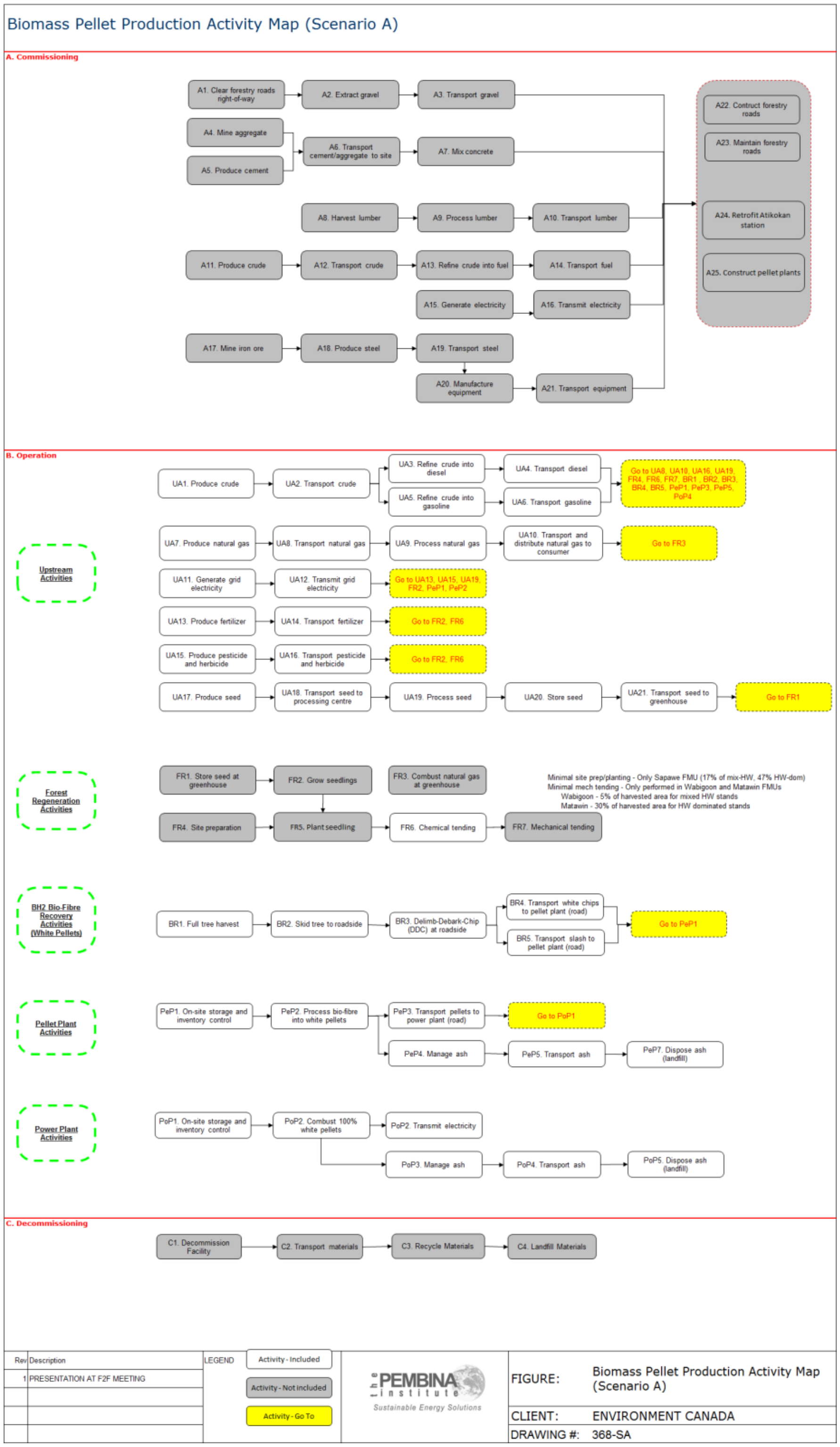
- Conifer-dominated stands are targeted as priority, but stands with greater hardwood content now also harvested.
- Hardwood utilization is approximately 70% of annual allowable cut (AAC) with 50% of hardwood dominated stands targeted for harvest.

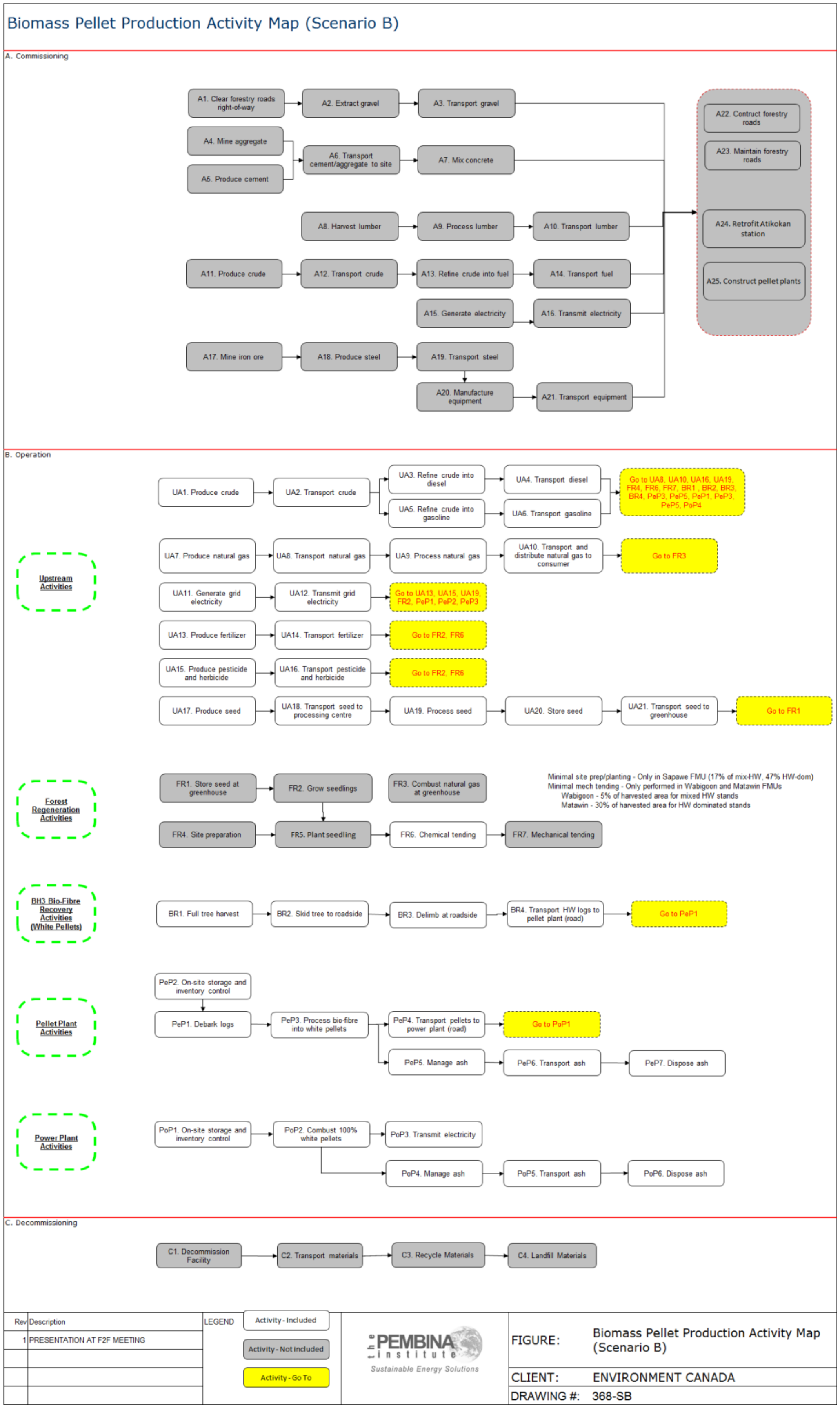
- Hardwood biomass is predominantly from DDC bush roadside operations (slightly higher proportion of DDC system compared to current practice)
- All hardwood chips would be used for white pellet production and residues from chipping operations would be hauled to facilities for the drying process in pellet production
- Roadside residues from the conventional full-tree harvest are not considered. Their levels should be similar to BH1 because the added biofibre supply comes from previously unharvested trees. It can still be used as a supply for a CHP or to produce brown pellets.

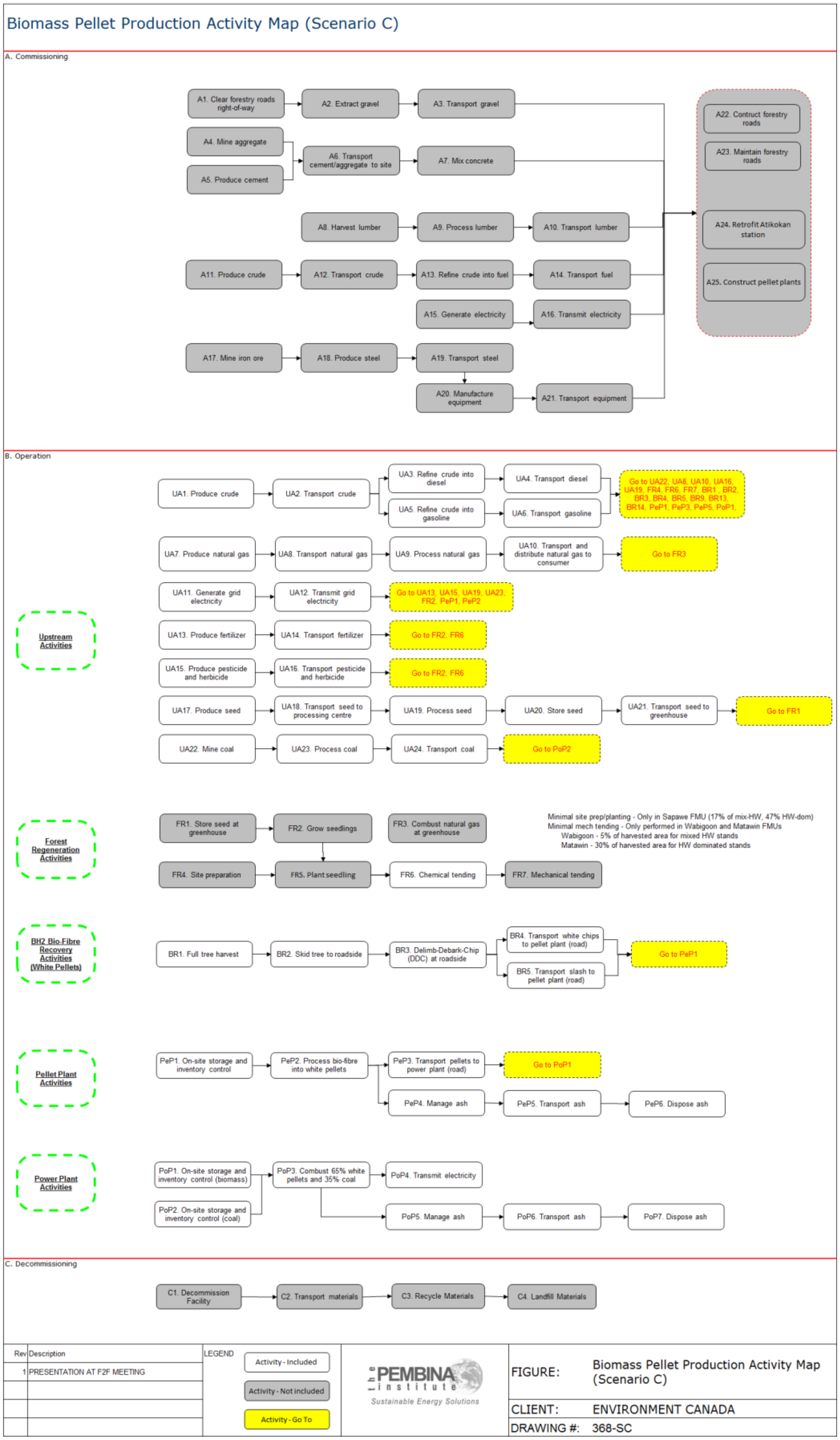
BH3 (full hardwood harvest)

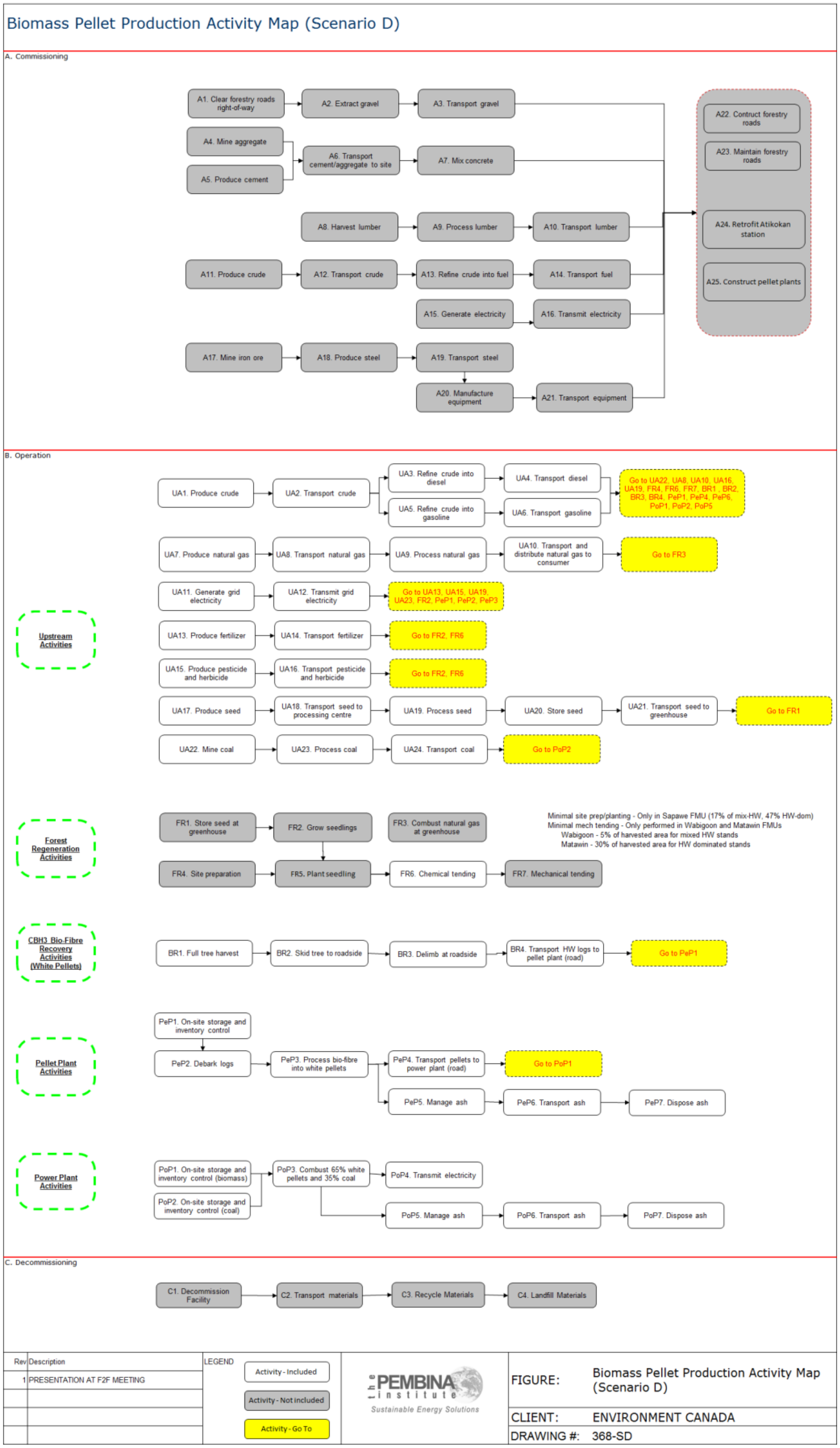
- Dedicated full-tree harvesting of hardwoods that are unmarketable or unmerchantable for conventional forest products but can be used for white pellet production.
- Both conifer-dominated stands and hardwood stands are targeted, with hardwood that is additional to current harvested amounts being used for biofibre for (white pellet production.
- Hardwood utilization is approximately 95% of annual allowable cut for hardwoods (the standard of 25 wildlife trees/ha to be left standing still need to be respected).
- Preferred harvest method is conventional full-tree-to-roadside, with logs delivered tree-length to pellet processing facility.
  - Logs are debarked and chipped at the facility with electric equipment
  - Debarking residues are used to dry the chips on site (aspen and birch logs have a bark content of 18% and 14% respectively
  - Delimbing residues from the hardwood harvesting operation could also be used as a source of feedstock if the bark from the hauled logs is not sufficient.
- Roadside residues from the conventional full-tree harvest are not considered. Their levels will be higher than for BH1 because the added biofibre supply comes from logs only of previously unharvested trees. All tops and branches from the previously unharvested trees will add to the residues pools. The added residues could be used as a supply for a CHP or to produce brown pellets.

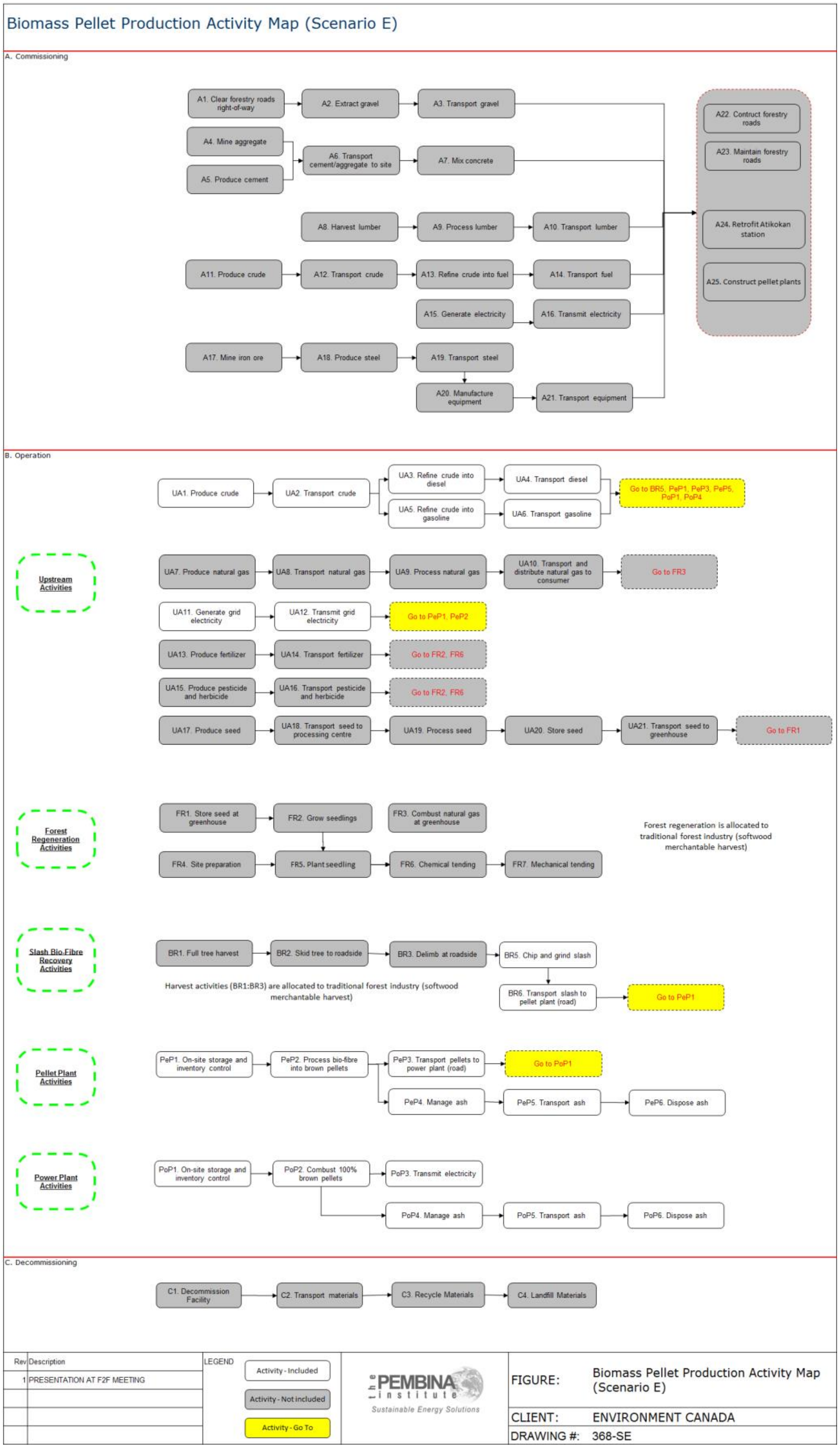
Appendix B. Life cycle activity maps



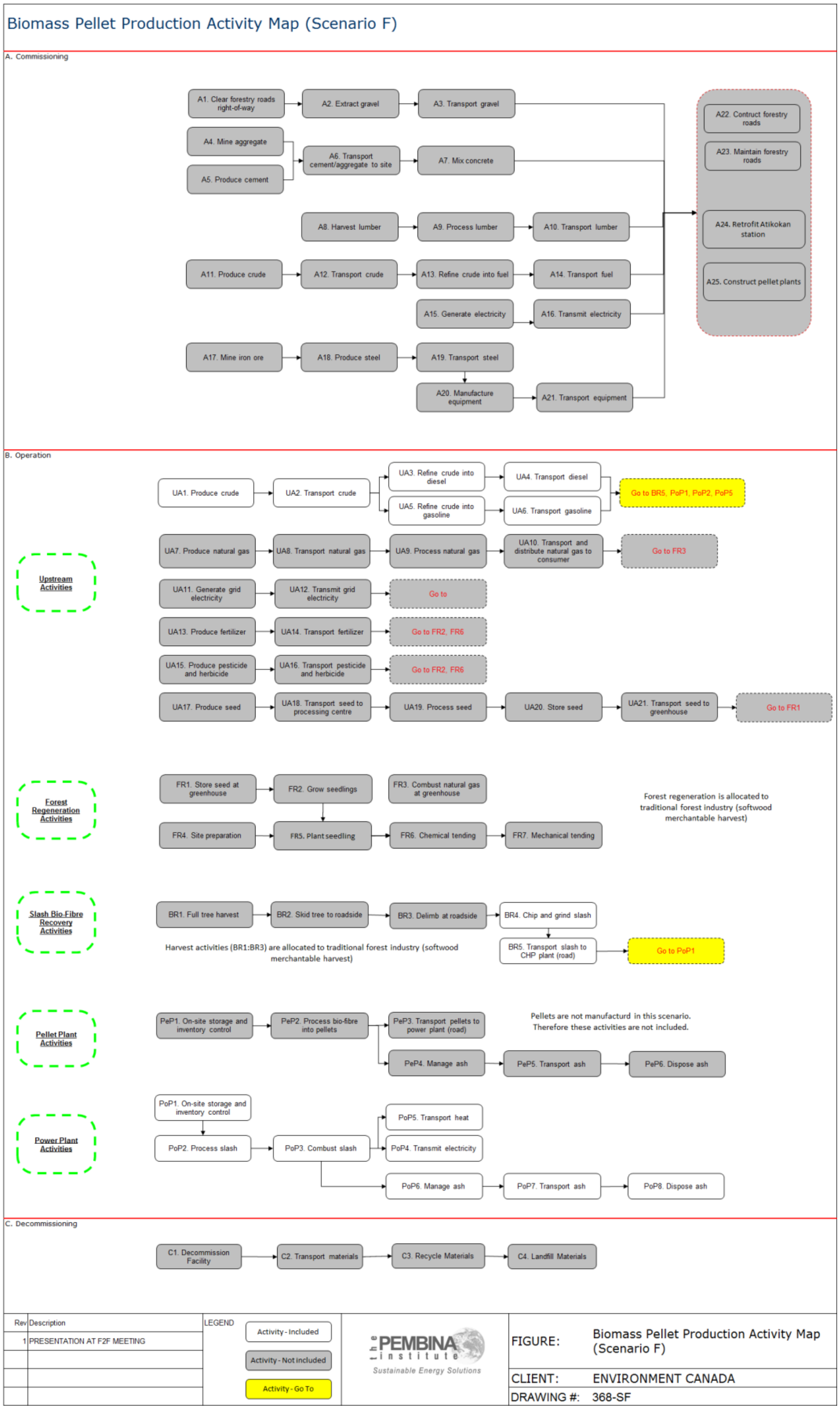

Biomass Pellet Production Activity Map (Scenario B)
A. Commissioning
A1. Clear forestry roads right-of-way
A2. Extract gravel
A3. Transport gravel
A4. Mine aggregate
A5. Produce cement
A6. Transport cement/aggregate to site
A7. Mix concrete
A8. Harvest lumber
A9. Process lumber
A10. Transport lumber
A11. Produce crude
A12. Transport crude
A13. Refine crude into fuel
A14. Transport fuel
A15. Generate electricity
A16. Transmit electricity
A17. Mine iron ore
A18. Produce steel
A19. Transport steel
A20. Manufacture equipment
A21. Transport equipment
A22. Contruct forestry roads
A23. Maintain forestry roads
A24. Retrofit Atikokan station
A25. Construct pellet plants
B. Operation
Upstream Activities
UA1. Produce crude
UA2. Transport crude
UA3. Refine crude into diesel
UA4. Transport diesel
UA5. Refine crude into gasoline
UA6. Transport gasoline
Go to UA8, UA10, UA16, UA19, FR4, FR6, FR7, BR1, BR2, BR3, BR4, PeP3, PeP5, PeP1, PeP3, PeP5, PoP4
UA7. Produce natural gas
UA8. Transport natural gas
UA9. Process natural gas
UA10. Transport and distribute natural gas to consumer
Go to FR3
UA11. Generate grid electricity
UA12. Transmit grid electricity
Go to UA13, UA15, UA19, FR2, PeP1, PeP2, PeP3
UA13. Produce fertilizer
UA14. Transport fertilizer
Go to FR2, FR6
UA15. Produce pesticide and herbicide
UA16. Transport pesticide and herbicide
Go to FR2, FR6
UA17. Produce seed
UA18. Transport seed to processing centre
UA19. Process seed
UA20. Store seed
UA21. Transport seed to greenhouse
Go to FR1
Forest Regeneration Activities
FR1. Store seed at greenhouse
FR2. Grow seedlings
FR3. Combust natural gas at greenhouse
Minimal site prep/planting - Only in Sapawe FMU (17% of mix-HW, 47% HW-dom)
Minimal mech tending - Only performed in Wabigoon and Matawin FMUs
Wabigoon - 5% of harvested area for mixed HW stands
Matawin - 30% of harvested area for HW dominated stands
FR4. Site preparation
FR5. Plant seedling
FR6. Chemical tending
FR7. Mechanical tending
BH3 Bio-Fibre Recovery Activities (White Pellets)
BR1. Full tree harvest
BR2. Skid tree to roadside
BR3. Delimb at roadside
BR4. Transport HW logs to pellet plant (road)
Go to PeP1
Pellet Plant Activities
PeP2. On-site storage and inventory control
PeP1. Debark logs
PeP3. Process bio-fibre into white pellets
PeP4. Transport pellets to power plant (road)
Go to PoP1
PeP5. Manage ash
PeP6. Transport ash
PeP7. Dispose ash
Power Plant Activities
PoP1. On-site storage and inventory control
PoP2. Combust 100% white pellets
PoP3. Transmit electricity
PoP4. Manage ash
PoP5. Transport ash
PoP6. Dispose ash
C. Decommissioning
C1. Decommission Facility
C2. Transport materials
C3. Recycle Materials
C4. Landfill Materials
Rev Description
1 PRESENTATION AT F2F MEETING
LEGEND
Activity - Included
Activity - Not included
Activity - Go To
the PEMBINA institute
Sustainable Energy Solutions
FIGURE: Biomass Pellet Production Activity Map (Scenario B)
CLIENT: ENVIRONMENT CANADA
DRAWING #: 368-SB

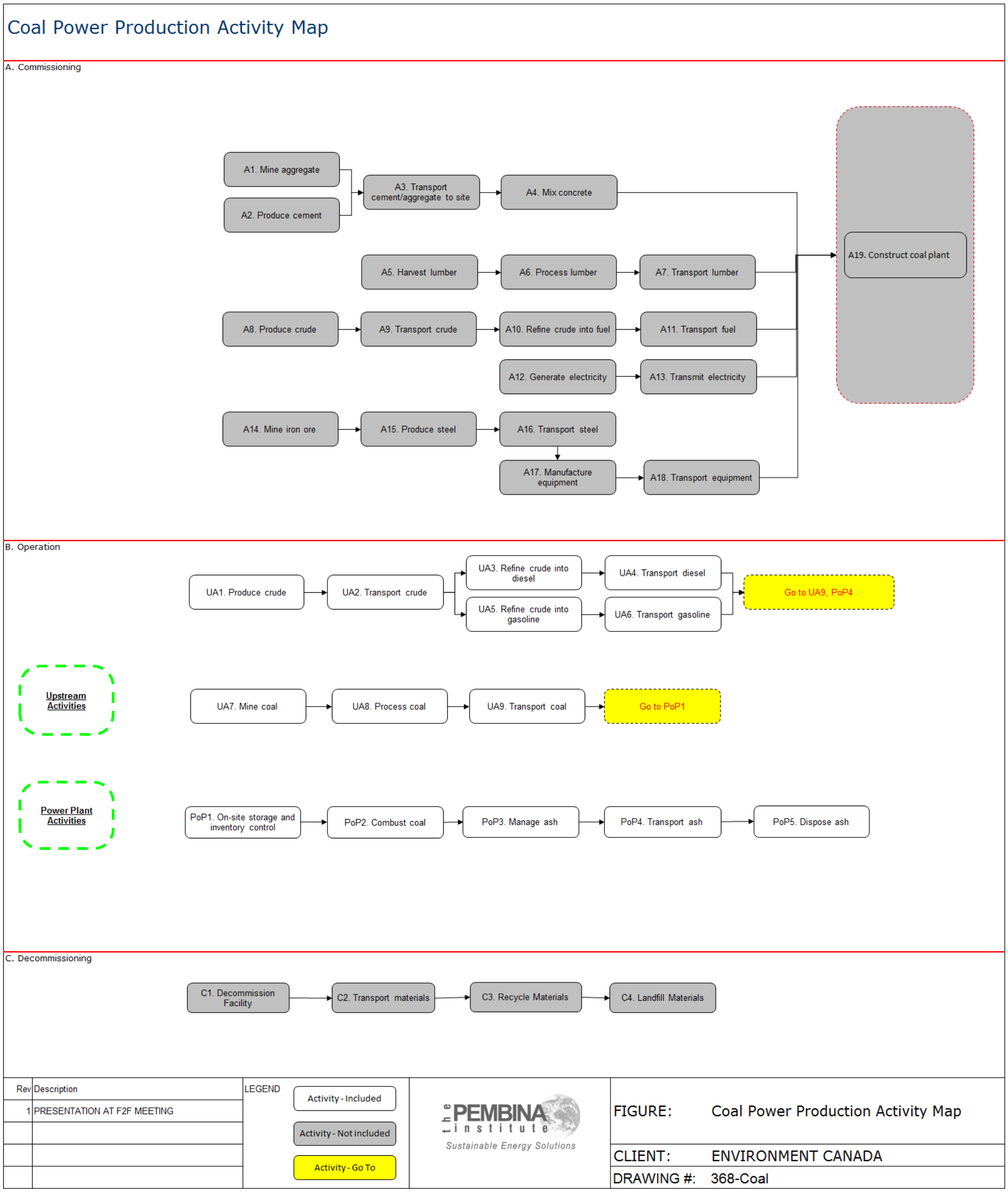

Biomass Pellet Production Activity Map (Scenario C)
A. Commissioning
A1. Clear forestry roads right-of-way
A2. Extract gravel
A3. Transport gravel
A4. Mine aggregate
A5. Produce cement
A6. Transport cement/aggregate to site
A7. Mix concrete
A8. Harvest lumber
A9. Process lumber
A10. Transport lumber
A11. Produce crude
A12. Transport crude
A13. Refine crude into fuel
A14. Transport fuel
A15. Generate electricity
A16. Transmit electricity
A17. Mine iron ore
A18. Produce steel
A19. Transport steel
A20. Manufacture equipment
A21. Transport equipment
A22. Contruct forestry roads
A23. Maintain forestry roads
A24. Retrofit Atikokan station
A25. Construct pellet plants
B. Operation
Upstream Activities
UA1. Produce crude
UA2. Transport crude
UA3. Refine crude into diesel
UA4. Transport diesel
UA5. Refine crude into gasoline
UA6. Transport gasoline
Go to UA22, UA8, UA10, UA16, UA19, FR4, FR6, FR7, BR1, BR2, BR3, BR4, BR5, BR9, BR13, BR14, PeP1, PeP3, PeP5, PoP1,
UA7. Produce natural gas
UA8. Transport natural gas
UA9. Process natural gas
UA10. Transport and distribute natural gas to consumer
Go to FR3
UA11. Generate grid electricity
UA12. Transmit grid electricity
Go to UA13, UA15, UA19, UA23, FR2, PeP1, PeP2
UA13. Produce fertilizer
UA14. Transport fertilizer
Go to FR2, FR6
UA15. Produce pesticide and herbicide
UA16. Transport pesticide and herbicide
Go to FR2, FR6
UA17. Produce seed
UA18. Transport seed to processing centre
UA19. Process seed
UA20. Store seed
UA21. Transport seed to greenhouse
Go to FR1
UA22. Mine coal
UA23. Process coal
UA24. Transport coal
Go to PoP2
Forest Regeneration Activities
FR1. Store seed at greenhouse
FR2. Grow seedlings
FR3. Combust natural gas at greenhouse
Minimal site prep/planting - Only in Sapawe FMU (17% of mix-HW, 47% HW-dom)
Minimal mech tending - Only performed in Wabigoon and Matawin FMUs
Wabigoon - 5% of harvested area for mixed HW stands
Matawin - 30% of harvested area for HW dominated stands
FR4. Site preparation
FR5. Plant seedling
FR6. Chemical tending
FR7. Mechanical tending
BH2 Bio-Fibre Recovery Activities (White Pellets)
BR1. Full tree harvest
BR2. Skid tree to roadside
BR3. Delimb-Debark-Chip (DDC) at roadside
BR4. Transport white chips to pellet plant (road)
BR5. Transport slash to pellet plant (road)
Go to PeP1
Pellet Plant Activities
PeP1. On-site storage and inventory control
PeP2. Process bio-fibre into white pellets
PeP3. Transport pellets to power plant (road)
Go to PoP1
PeP4. Manage ash
PeP5. Transport ash
PeP6. Dispose ash
Power Plant Activities
PoP1. On-site storage and inventory control (biomass)
PoP2. On-site storage and inventory control (coal)
PoP3. Combust 65% white pellets and 35% coal
PoP4. Transmit electricity
PoP5. Manage ash
PoP6. Transport ash
PoP7. Dispose ash
C. Decommissioning
C1. Decommission Facility
C2. Transport materials
C3. Recycle Materials
C4. Landfill Materials
Rev Description
1 PRESENTATION AT F2F MEETING
LEGEND
Activity - Included
Activity - Not included
Activity - Go To
the PEMBINA institute
Sustainable Energy Solutions
FIGURE: Biomass Pellet Production Activity Map (Scenario C)
CLIENT: ENVIRONMENT CANADA
DRAWING #: 368-SC


Biomass Pellet Production Activity Map (Scenario D)
A. Commissioning
A1. Clear forestry roads right-of-way
A2. Extract gravel
A3. Transport gravel
A4. Mine aggregate
A5. Produce cement
A6. Transport cement/aggregate to site
A7. Mix concrete
A8. Harvest lumber
A9. Process lumber
A10. Transport lumber
A11. Produce crude
A12. Transport crude
A13. Refine crude into fuel
A14. Transport fuel
A15. Generate electricity
A16. Transmit electricity
A17. Mine iron ore
A18. Produce steel
A19. Transport steel
A20. Manufacture equipment
A21. Transport equipment
A22. Contruct forestry roads
A23. Maintain forestry roads
A24. Retrofit Atikokan station
A25. Construct pellet plants
B. Operation
Upstream Activities
UA1. Produce crude
UA2. Transport crude
UA3. Refine crude into diesel
UA4. Transport diesel
UA5. Refine crude into gasoline
UA6. Transport gasoline
Go to UA22, UA8, UA10, UA16, UA19, FR4, FR6, FR7, BR1 , BR2, BR3, BR4, PeP1, PeP4, PeP6, PoP1, PoP2, PoP5
UA7. Produce natural gas
UA8. Transport natural gas
UA9. Process natural gas
UA10. Transport and distribute natural gas to consumer
Go to FR3
UA11. Generate grid electricity
UA12. Transmit grid electricity
Go to UA13, UA15, UA19, UA23, FR2, PeP1, PeP2, PeP3
UA13. Produce fertilizer
UA14. Transport fertilizer
Go to FR2, FR6
UA15. Produce pesticide and herbicide
UA16. Transport pesticide and herbicide
Go to FR2, FR6
UA17. Produce seed
UA18. Transport seed to processing centre
UA19. Process seed
UA20. Store seed
UA21. Transport seed to greenhouse
Go to FR1
UA22. Mine coal
UA23. Process coal
UA24. Transport coal
Go to PoP2
Forest Regeneration Activities
FR1. Store seed at greenhouse
FR2. Grow seedlings
FR3. Combust natural gas at greenhouse
Minimal site prep/planting - Only in Sapawe FMU (17% of mix-HW, 47% HW-dom)
Minimal mech tending - Only performed in Wabigoon and Matawin FMUs
Wabigoon - 5% of harvested area for mixed HW stands
Matawin - 30% of harvested area for HW dominated stands
FR4. Site preparation
FR5. Plant seedling
FR6. Chemical tending
FR7. Mechanical tending
CBH3 Bio-Fibre Recovery Activities (White Pellets)
BR1. Full tree harvest
BR2. Skid tree to roadside
BR3. Delimb at roadside
BR4. Transport HW logs to pellet plant (road)
Go to PeP1
Pellet Plant Activities
PeP1. On-site storage and inventory control
PeP2. Debark logs
PeP3. Process bio-fibre into white pellets
PeP4. Transport pellets to power plant (road)
Go to PoP1
PeP5. Manage ash
PeP6. Transport ash
PeP7. Dispose ash
Power Plant Activities
PoP1. On-site storage and inventory control (biomass)
PoP2. On-site storage and inventory control (coal)
PoP3. Combust 65% white pellets and 35% coal
PoP4. Transmit electricity
PoP5. Manage ash
PoP6. Transport ash
PoP7. Dispose ash
C. Decommissioning
C1. Decommission Facility
C2. Transport materials
C3. Recycle Materials
C4. Landfill Materials
Rev Description
1 PRESENTATION AT F2F MEETING
LEGEND
Activity - Included
Activity - Not included
Activity - Go To
the PEMBINA institute
Sustainable Energy Solutions
FIGURE: Biomass Pellet Production Activity Map (Scenario D)
CLIENT: ENVIRONMENT CANADA
DRAWING #: 368-SD



Biomass Pellet Production Activity Map (Scenario E)
A. Commissioning
A1. Clear forestry roads right-of-way
A2. Extract gravel
A3. Transport gravel
A4. Mine aggregate
A5. Produce cement
A6. Transport cement/aggregate to site
A7. Mix concrete
A8. Harvest lumber
A9. Process lumber
A10. Transport lumber
A11. Produce crude
A12. Transport crude
A13. Refine crude into fuel
A14. Transport fuel
A15. Generate electricity
A16. Transmit electricity
A17. Mine iron ore
A18. Produce steel
A19. Transport steel
A20. Manufacture equipment
A21. Transport equipment
A22. Contruct forestry roads
A23. Maintain forestry roads
A24. Retrofit Atikokan station
A25. Construct pellet plants
B. Operation
Upstream Activities
UA1. Produce crude
UA2. Transport crude
UA3. Refine crude into diesel
UA4. Transport diesel
UA5. Refine crude into gasoline
UA6. Transport gasoline
Go to BR5, PeP1, PeP3, PeP5, PoP1, PoP4
UA7. Produce natural gas
UA8. Transport natural gas
UA9. Process natural gas
UA10. Transport and distribute natural gas to consumer
Go to FR3
UA11. Generate grid electricity
UA12. Transmit grid electricity
Go to PeP1, PeP2
UA13. Produce fertilizer
UA14. Transport fertilizer
Go to FR2, FR6
UA15. Produce pesticide and herbicide
UA16. Transport pesticide and herbicide
Go to FR2, FR6
UA17. Produce seed
UA18. Transport seed to processing centre
UA19. Process seed
UA20. Store seed
UA21. Transport seed to greenhouse
Go to FR1
Forest Regeneration Activities
FR1. Store seed at greenhouse
FR2. Grow seedlings
FR3. Combust natural gas at greenhouse
FR4. Site preparation
FR5. Plant seedling
FR6. Chemical tending
FR7. Mechanical tending
Forest regeneration is allocated to traditional forest industry (softwood merchantable harvest)
Slash Bio-Fibre Recovery Activities
BR1. Full tree harvest
BR2. Skid tree to roadside
BR3. Delimb at roadside
BR5. Chip and grind slash
BR6. Transport slash to pellet plant (road)
Go to PeP1
Harvest activities (BR1:BR3) are allocated to traditional forest industry (softwood merchantable harvest)
Pellet Plant Activities
PeP1. On-site storage and inventory control
PeP2. Process bio-fibre into brown pellets
PeP3. Transport pellets to power plant (road)
Go to PoP1
PeP4. Manage ash
PeP5. Transport ash
PeP6. Dispose ash
Power Plant Activities
PoP1. On-site storage and inventory control
PoP2. Combust 100% brown pellets
PoP3. Transmit electricity
PoP4. Manage ash
PoP5. Transport ash
PoP6. Dispose ash
C. Decommissioning
C1. Decommission Facility
C2. Transport materials
C3. Recycle Materials
C4. Landfill Materials
Rev Description
1 PRESENTATION AT F2F MEETING
LEGEND
Activity - Included
Activity - Not included
Activity - Go To
the PEMBINA institute
Sustainable Energy Solutions
FIGURE: Biomass Pellet Production Activity Map (Scenario E)
CLIENT: ENVIRONMENT CANADA
DRAWING #: 368-SE


Biomass Pellet Production Activity Map (Scenario F)
A. Commissioning
A1. Clear forestry roads right-of-way
A2. Extract gravel
A3. Transport gravel
A4. Mine aggregate
A5. Produce cement
A6. Transport cement/aggregate to site
A7. Mix concrete
A8. Harvest lumber
A9. Process lumber
A10. Transport lumber
A11. Produce crude
A12. Transport crude
A13. Refine crude into fuel
A14. Transport fuel
A15. Generate electricity
A16. Transmit electricity
A17. Mine iron ore
A18. Produce steel
A19. Transport steel
A20. Manufacture equipment
A21. Transport equipment
A22. Contruct forestry roads
A23. Maintain forestry roads
A24. Retrofit Atikokan station
A25. Construct pellet plants
B. Operation
Upstream Activities
UA1. Produce crude
UA2. Transport crude
UA3. Refine crude into diesel
UA4. Transport diesel
UA5. Refine crude into gasoline
UA6. Transport gasoline
Go to BR5, PoP1, PoP2, PoP5
UA7. Produce natural gas
UA8. Transport natural gas
UA9. Process natural gas
UA10. Transport and distribute natural gas to consumer
Go to FR3
UA11. Generate grid electricity
UA12. Transmit grid electricity
Go to
UA13. Produce fertilizer
UA14. Transport fertilizer
Go to FR2, FR6
UA15. Produce pesticide and herbicide
UA16. Transport pesticide and herbicide
Go to FR2, FR6
UA17. Produce seed
UA18. Transport seed to processing centre
UA19. Process seed
UA20. Store seed
UA21. Transport seed to greenhouse
Go to FR1
Forest Regeneration Activities
FR1. Store seed at greenhouse
FR2. Grow seedlings
FR3. Combust natural gas at greenhouse
FR4. Site preparation
FR5. Plant seedling
FR6. Chemical tending
FR7. Mechanical tending
Forest regeneration is allocated to traditional forest industry (softwood merchantable harvest)
Slash Bio-Fibre Recovery Activities
BR1. Full tree harvest
BR2. Skid tree to roadside
BR3. Delimb at roadside
BR4. Chip and grind slash
BR5. Transport slash to CHP plant (road)
Go to PoP1
Harvest activities (BR1:BR3) are allocated to traditional forest industry (softwood merchantable harvest)
Pellet Plant Activities
PeP1. On-site storage and inventory control
PeP2. Process bio-fibre into pellets
PeP3. Transport pellets to power plant (road)
Pellets are not manufactured in this scenario. Therefore these activities are not included.
PeP4. Manage ash
PeP5. Transport ash
PeP6. Dispose ash
Power Plant Activities
PoP1. On-site storage and inventory control
PoP2. Process slash
PoP3. Combust slash
PoP5. Transport heat
PoP4. Transmit electricity
PoP6. Manage ash
PoP7. Transport ash
PoP8. Dispose ash
C. Decommissioning
C1. Decommission Facility
C2. Transport materials
C3. Recycle Materials
C4. Landfill Materials
Rev Description
1 PRESENTATION AT F2F MEETING
LEGEND
Activity - Included
Activity - Not included
Activity - Go To
the PEMBINA institute
Sustainable Energy Solutions
FIGURE: Biomass Pellet Production Activity Map (Scenario F)
CLIENT: ENVIRONMENT CANADA
DRAWING #: 368-SF


Coal Power Production Activity Map
A. Commissioning
A1. Mine aggregate
A2. Produce cement
A3. Transport cement/aggregate to site
A4. Mix concrete
A5. Harvest lumber
A6. Process lumber
A7. Transport lumber
A8. Produce crude
A9. Transport crude
A10. Refine crude into fuel
A11. Transport fuel
A12. Generate electricity
A13. Transmit electricity
A14. Mine iron ore
A15. Produce steel
A16. Transport steel
A17. Manufacture equipment
A18. Transport equipment
A19. Construct coal plant
B. Operation
UA1. Produce crude
UA2. Transport crude
UA3. Refine crude into diesel
UA4. Transport diesel
UA5. Refine crude into gasoline
UA6. Transport gasoline
Go to UA9, PoP4
Upstream Activities
UA7. Mine coal
UA8. Process coal
UA9. Transport coal
Go to PoP1
Power Plant Activities
PoP1. On-site storage and inventory control
PoP2. Combust coal
PoP3. Manage ash
PoP4. Transport ash
PoP5. Dispose ash
C. Decommissioning
C1. Decommission Facility
C2. Transport materials
C3. Recycle Materials
C4. Landfill Materials
Rev
Description
1
PRESENTATION AT F2F MEETING
LEGEND
Activity - Included
Activity - Not included
Activity - Go To
the PEMBINA institute
Sustainable Energy Solutions
FIGURE: Coal Power Production Activity Map
CLIENT: ENVIRONMENT CANADA
DRAWING #: 368-Coal

Appendix C. Allocation notes

C.1. Meeting overview

Pembina and Conestoga Rovers (CRA) are convening this session to obtain the Advisory Committee's input on allocation decisions that are being made. During this meeting we intend to provide background on the situation and our current reasoning and justifications. We are looking to the advisory committee members (this group) for input and approval. We may request your assistance again further down the road.

Allocation is being considered at the cogeneration plant in Scenario F and for the collection of softwood slash in biofibre harvest scenario 1 (slash that is used to manufacture brown pellets).

C.2. Meeting objectives

1. To familiarize this team on the allocation background and issues.
2. To build a team consensus on the appropriate methodology for this project.

C.3. ISO refresher on allocation

- ISO considers it to be a last resort and prefers a "system expansion" approach.
- In system expansion, all pathways must produce the same products. For pathways that do not produce all products, their scope is expanded to include an equivalent process.
- Allocation can be performed using a number or methods (e.g. economic value, energy, mass)
    - Choice of allocation method means that choice is subjective.

C.4. CHP plant allocation

- Primary goal of this project is to compare biomass pellet combustion for power generation.
- CHP case is a fringe case based on RFP and current project scope.
- The CHP case raises an issue because it produces two products (heat & power) when the other scenarios only produce one product (power). A fair life cycle assessment will compare options fairly that have the same outputs (termed "functional units").
- Options:
    - **Option1**: Allocate CHP impacts based on a given ratio to the electricity production. In conjunction, perform a sensitivity analysis on the allocation method and %.

  - **Option2**: Perform a system expansion to include heat generating process for Scenarios A/B/C/D/E/coal/NG. The heat could be delivered using natural gas or bio-fibre.
- Pros to allocating (Option 1 above):
  - More consistent with the goals of this project being to evaluate biomass for power generation.
  - Adding a heat process to the power generation scenarios (i.e. scenarios A to E) will “muddy” the results. To compare scenarios against the CHP pathway, biomass electricity will need to add heat data.
  - Allocation is a simpler solution. Data for the heat case (extraction, processing, transportation, combustion) will not require modeling.
- Cons to allocating:
  - ISO recommends allocation as last resort. Prefers system expansion because less subjective assumptions to be made.
- Recommendation:
  - The goal of the project is primarily focused on biomass for power generation.
  - If a system expansion is performed then we’d add together power from biomass with NG heat to compare against the CHP case. With generic NG data on water/soil/wildlife, this will “muddy” the summation.
  - Therefore recommended action is to allocate at the CHP and run a sensitivity using different allocation methods.

Meeting notes:

- Allocation is a good way to go for this case. The concern comes through system expansion by complicating the scenario with NG production. In reality, this wouldn’t be an option for a company to choose. They would look at flue gas and use heat exchanger. Any NG for heat production to meet requirements for CHP is not technically viable or preferred option.
- Sebnem’s recommendation to recognize CHP. There were specific examples in our mind to go with CHP such as pulp and paper mills in close proximity to Atikokan. They work in cogen mode to use steam. Primary objective is power but also have some comparison data to compare to cogen application.
- Typically when we look at biomass hog fuel to power production, the efficiency is around 25%. Having capture of heat application and putting applying 25% factor to it. Could add in to CHP by capturing heat that is generated.
- Could use “combined cycle” approach. Re-configuring the efficiency of conversion.
- If we are only to look at the cogen power, it is a relatively small portion of it. The overall efficiency is much higher if there is enough thermal load to put energy into.
- Efficiency will be lower. In cogen, if there are 2 products. It is optimized for heat. Power is the co-beneficial product.

- Power plant, fuel is much more uniform and dry. Those differences will build up and show results of cogen not as good as it could be.
- GHG Protocol. They have something called the "efficiency method" for cogeneration. They use typical elect efficiency and make that into allocation. Apply efficiency factor into allocation. Cogen becomes meaningless in this context. Cogen with district heating or other uses, thermal will be primary objective and power is adjusted accordingly.

Summary:

- Choose one most appropriate cogen case and test with sensitivities in appendix.
- Go with option 1 above but refined. Adjust the proposed cogen case based on Sebnem's comments. Will ask Sebnem for direction and review of cogen modeling.
- Test results with sensitivities.

C.5. Softwood harvest slash

- For biofibre harvest scenario 1, slash from traditional softwood harvest is left at roadside as waste. Our understanding of current practice is that this slash is either left at roadside or is burned at roadside. This project models the collection of this slash as a feedstock for pellets.
- FP Innovations has calculated some environmental impacts (i.e. GHGs) for forestry operations for all six biomass combustion scenarios. They intended to exclude the softwood harvest, skidding to roadside and delimbing activities in their calculations. For the hardwood harvest, they intended to include the harvest, skidding, delimbing and chipping activities (i.e. all forest activities).
- For softwoods, we would ideally calculate the impacts for all forestry activities (harvest, skid, delimb) and allocate a fair portion to the slash. Once the slash has a useful purpose or economic value, it should no longer be considered waste.
- A large problem is data availability. There are currently questions surrounding what activities are included/excluded in the FPInnovations project.
- The goal of this project is to obtain data that closely resembles actual operations in the Atikokan region. We are prioritizing local data much higher than from other jurisdictions. Without data from FP Innovations, we may have to model using U.S. or European harvest-skid-slash data or use FP Innovations hardwood harvest-slash-skid data as a surrogate.
- Options:
    - System expansion is not an option here.
    - **Option1**: Use FP Innovations softwood harvest data if it is available.
    - **Option2**: If FP Innovations softwood data is not available, attribute impacts to slash using FP Innovations hardwood data.
    - **Option3**: Use data from other geographical regions (U.S. or Europe).

    - **Option4**: Assume it is a waste product. Test this assumption with sensitivity analysis using what data is available.

- Recommendation:
    - Progress through Options 1 to 3 sequentially. However, we'd mostly likely use FP Innovation's hardwood data as a surrogate for softwood harvest.

Meeting notes:

- FP Innovations for softwood only will be available. Use mass or economic value. Could do mass for data. Or Use option 4 to see how it will impact the results. If don't have Canadian data, can use CORRIM (equivalent of Athena for US). Forest operations for softwood and hardwood.
- Interesting discussion from a policy standpoint is if you want to do option 4. Policy makers would want to see it as a waste product versus not. Instead of assuming it is a waste, you could say "considering that harvesting emissions consider it a by-product". Consider it as an "anyways" resource.
- Use Corrim and FPI data as basis for sensitivity analysis.
- It is going to happen anyways and need to allocate impacts. Economic value is temporally unstable → price can change. Recommend using mass first. Use a "waste" sensitivity to see if it changes results.
- Given context of this analysis, need to be careful how to word it. Slash wouldn't ever be considered a "waste' product since it has value as habitat. Is it there anyways or is it a raw material with some environment burden. Interesting question to address using sensitivities.

Summary:

- Use FP Innovations data as first source for emissions and amend with Corrim.
- Allocate based on mass first and test with sensitivity on economic value.
- Also test sensitivity of assuming that slash is available without environmental burden to address interesting policy question.

Appendix D. Environmental impacts – Detailed results

This Appendix summarizes the environmental impacts for each bioenergy scenario and the coal reference case.

For the bioenergy scenario cases, since the *Forest Carbon* component for the Climate Change (tonnes CO_2e / MWh) is time dependent over the planning horizon, the average value has been selected and included in the table.

D.1. Coal Reference Case

Table 57. Environmental Impacts – Coal Reference Case

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA Results	Commissioning	0.0072	0.0312	0.0009	0.0012	0.0027	0.0022	0.0032
	Mine / Process / Transport	0.0354	0.2955	0.1770	0.0044	0.0825	0.1859	0.1932
	Coal combustion	1.2101	6.1247	0.0001	0.0080	0.0031	0.0009	0.0008
	Power Plant	0.0008	0.0042	0.0000	0.0015	0.1541	0.0006	-0.0045
	Total	**1.2534**	**6.4556**	**0.1780**	**0.0151**	**0.2423**	**0.1896**	**0.1927**

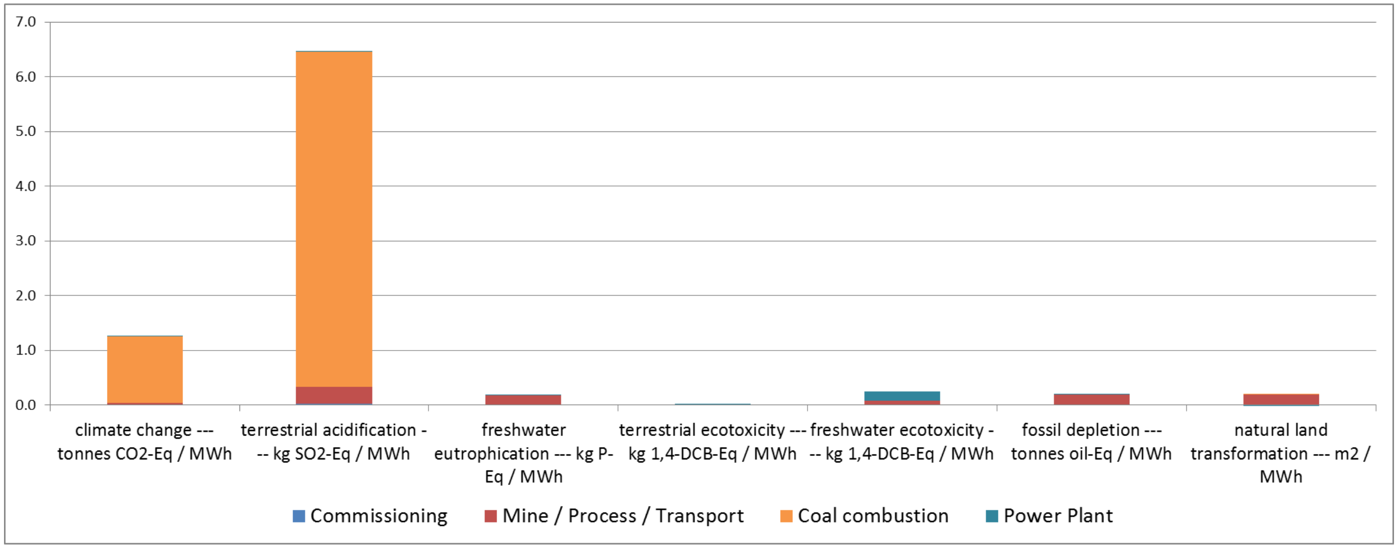


Figure 65. Environmental Impacts – Coal Reference Case

D.2. Bioenergy scenario A

Table 58. Environmental Impacts – bioenergy scenario A

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	0.0178	0.0800	0.0022	0.0030	0.0071	0.0056	0.0082
	Forest Regeneration	0.0041	0.0246	0.0000	0.0004	0.0018	0.0014	0.0020
	Bioharvest Recovery	0.0680	0.1980	0.0005	0.0059	0.0194	0.0136	0.0157
	Pellet Plant	0.0199	0.2695	0.0019	0.0182	0.0129	0.0049	0.0041
	Power Plant	0.0218	0.5640	0.0000	0.0293	0.0086	0.0000	-0.0001
	LCA Total	0.1316	1.1360	0.0047	0.0569	0.0498	0.0256	0.0299
	Forest Carbon (avg. 100 years)	1.1326						
Total		**1.2642**	**1.1360**	**0.0047**	**0.0569**	**0.0498**	**0.0256**	**0.0299**

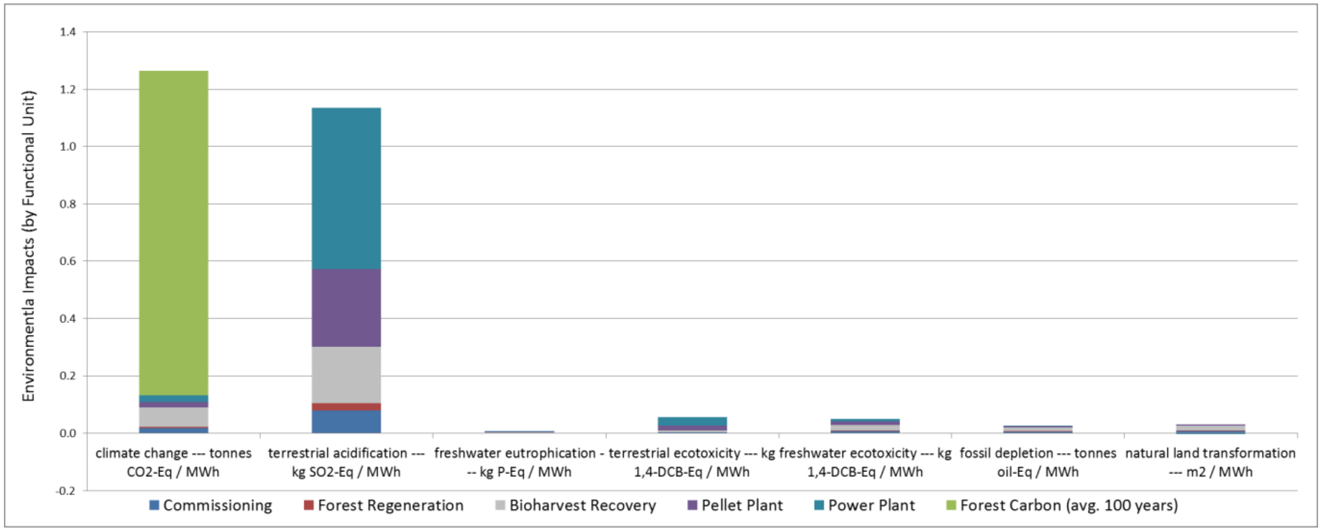


Figure 66. Environmental Impacts – bioenergy scenario A

D.3. Bioenergy scenario B

Table 59. Environmental Impacts – bioenergy scenario B

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	0.0090	0.0418	0.0011	0.0016	0.0038	0.0029	0.0042
	Forest Regeneration	0.0022	0.0129	0.0000	0.0002	0.0009	0.0008	0.0011
	Bioharvest Recovery	0.0308	0.0870	0.0003	0.0042	0.0121	0.0078	0.0083
	Pellet Plant	0.0218	0.2830	0.0020	0.0187	0.0207	0.0056	0.0048
	Power Plant	0.0218	0.5640	0.0000	0.0293	0.0086	0.0000	-0.0001
	LCA Total	0.0856	0.9887	0.0035	0.0541	0.0461	0.0171	0.0183
	100 years)	1.0245						
Total		**1.1101**	**0.9887**	**0.0035**	**0.0541**	**0.0461**	**0.0171**	**0.0183**

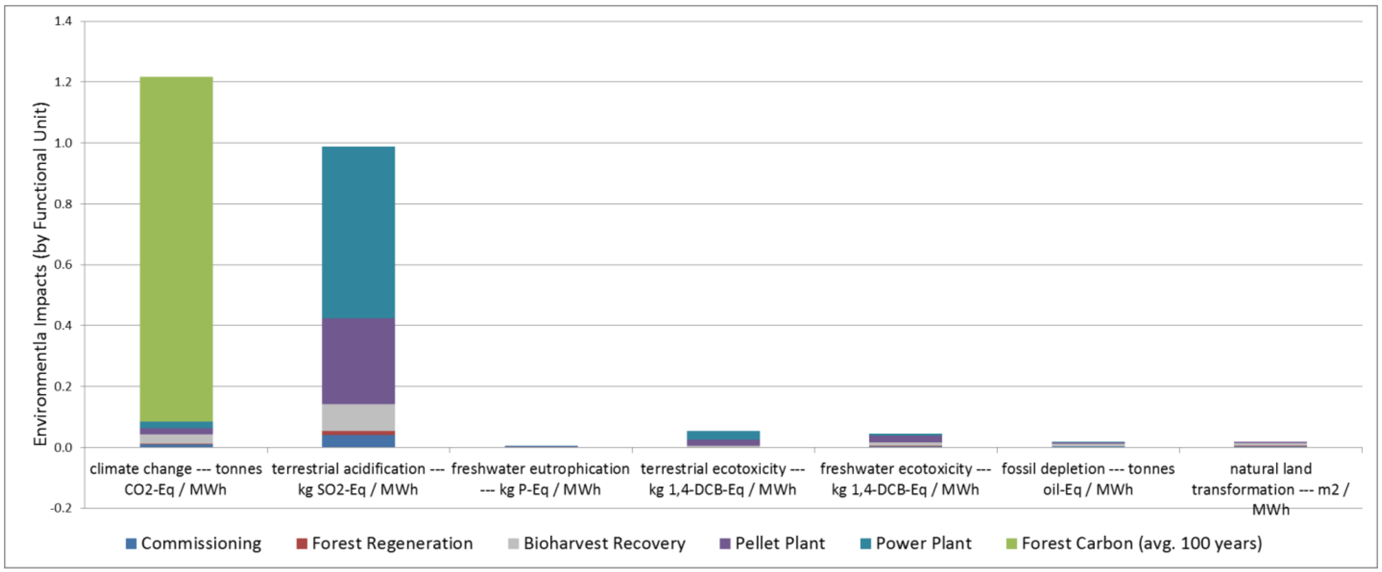


Figure 67. Environmental Impacts – bioenergy scenario B

D.4. Bioenergy scenario C

Table 60. Environmental Impacts – bioenergy scenario C

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	0.0023	0.0116	0.0003	0.0004	0.0011	0.0008	0.0012
	Mine / Process / Tran	0.0128	0.1067	0.0639	0.0016	0.0298	0.0671	0.0103
	Forest Regeneration	0.0026	0.0157	0.0000	0.0002	0.0012	0.0009	0.0013
	Bioharvest Recovery	0.0433	0.1263	0.0003	0.0038	0.0124	0.0087	0.0100
	Pellet Plant	0.0127	0.1719	0.0012	0.0116	0.0082	0.0032	0.0026
	Coal combustion	0.4235	2.1436	0.0000	0.0028	0.0011	0.0003	0.0003
	Power Plant	0.0142	0.3612	0.0000	0.0193	0.0611	0.0002	-0.0017
	LCA Total	0.5114	2.9370	0.0658	0.0397	0.1148	0.0811	0.0240
	Forest Carbon (avg. 100 years)	0.7224						
Total		**1.2338**	**2.9370**	**0.0658**	**0.0397**	**0.1148**	**0.0811**	**0.0240**

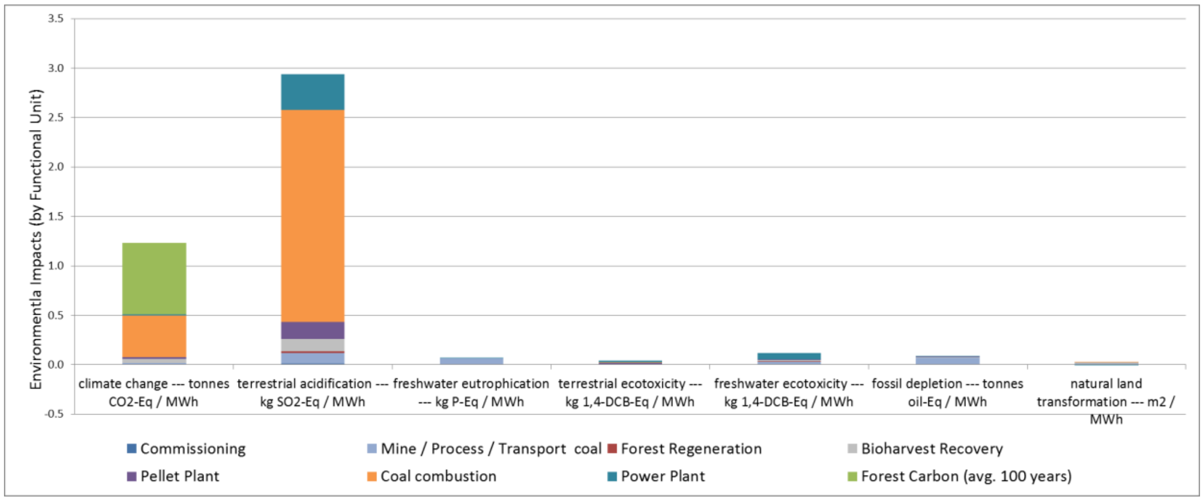


Figure 68. Environmental Impacts – bioenergy scenario C

D.5. Bioenergy scenario D

Table 61. Environmental Impacts – bioenergy scenario D

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	0.0012	0.0068	0.0001	0.0003	0.0007	0.0004	0.0007
	Mine / Process / Tran	0.0128	0.1067	0.0639	0.0016	0.0298	0.0671	0.0103
	Forest Regeneration	0.0014	0.0082	0.0000	0.0001	0.0006	0.0005	0.0007
	Bioharvest Recovery	0.0197	0.0555	0.0002	0.0027	0.0077	0.0050	0.0053
	Pellet Plant	0.0139	0.1805	0.0013	0.0120	0.0132	0.0036	0.0031
	Coal combustion	0.4235	2.1436	0.0000	0.0028	0.0011	0.0003	0.0003
	Power Plant	0.0142	0.3612	0.0000	0.0193	0.0611	0.0002	-0.0017
	LCA Total	0.4866	2.8625	0.0656	0.0387	0.1141	0.0771	0.0186
	Forest Carbon (avg. 100 years)	0.6534						
Total		**1.1400**	**2.8625**	**0.0656**	**0.0387**	**0.1141**	**0.0771**	**0.0186**

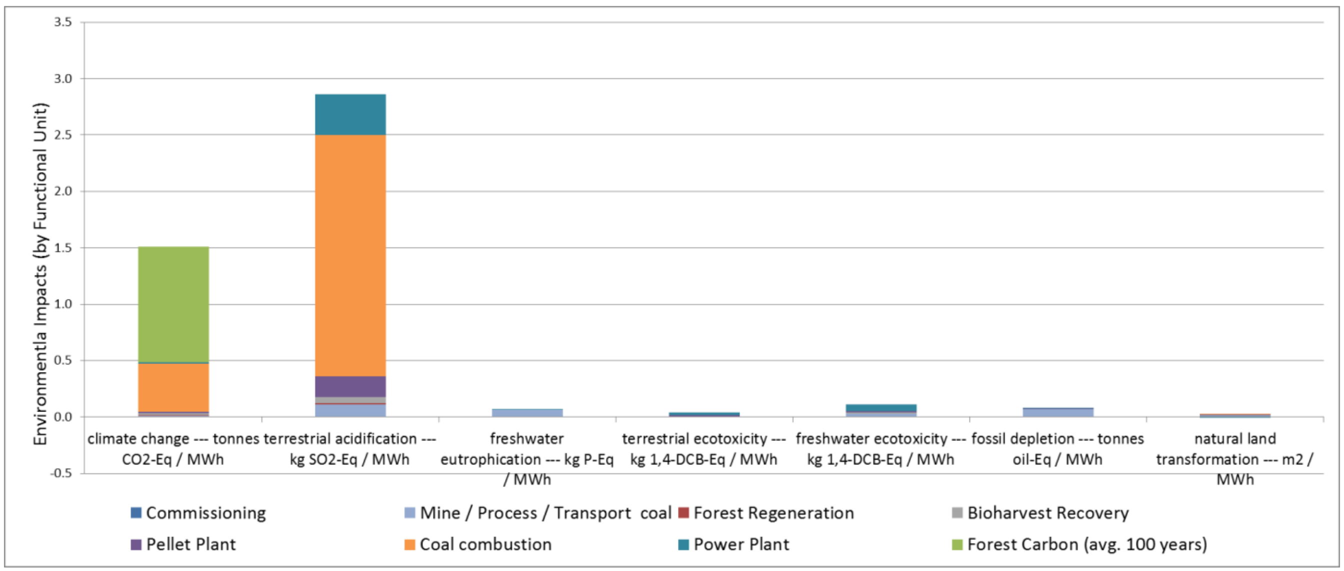


Figure 69. Environmental Impacts – bioenergy scenario D

D.6. Bioenergy scenario E

Table 62. Environmental Impacts – bioenergy scenario E

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	0.0137	0.0595	0.0017	0.0022	0.0052	0.0042	0.0062
	Forest Regeneration	0.0010	0.0059	0.0000	0.0001	0.0004	0.0003	0.0005
	Bioharvest Recovery	0.0276	-0.2837	0.0005	0.0038	0.0138	0.0104	0.0111
	Pellet Plant	0.0189	0.2496	0.0019	0.0173	0.0133	0.0047	0.0039
	Power Plant	0.0220	0.5652	0.0001	0.0294	0.0316	0.0001	-0.0005
	LCA Total	0.0831	0.5965	0.0041	0.0527	0.0643	0.0197	0.0212
	Forest Carbon (avg. 1	0.3435						
Total		**0.4266**	**0.5965**	**0.0041**	**0.0527**	**0.0643**	**0.0197**	**0.0212**

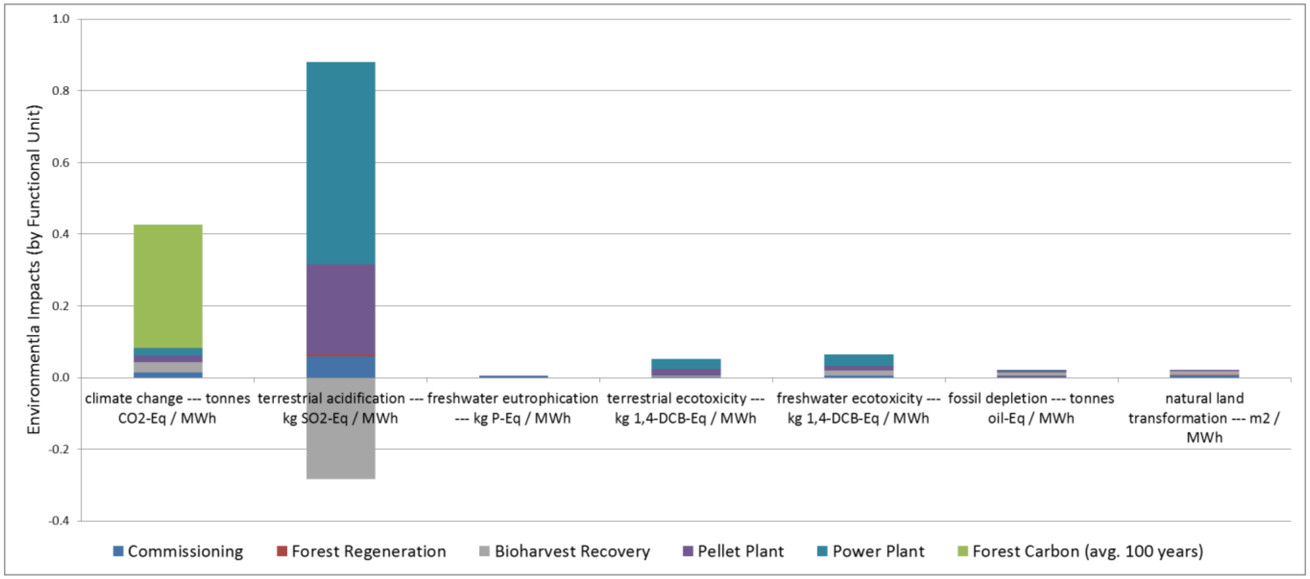


Figure 70. Environmental Impacts – bioenergy scenario E

D.7. Bioenergy scenario F

Table 63. Environmental Impacts – bioenergy scenario F

		climate change --- tonnes CO2-Eq / MWh	terrestrial acidification --- kg SO2-Eq / MWh	freshwater eutrophication --- kg P-Eq / MWh	terrestrial ecotoxicity --- kg 1,4-DCB-Eq / MWh	freshwater ecotoxicity --- kg 1,4-DCB-Eq / MWh	fossil depletion --- tonnes oil-Eq / MWh	natural land transformation --- m2 / MWh
LCA results	Commissioning	0.0001	0.0006	0.0000	0.0000	0.0001	0.0000	0.0002
	Forest Regeneration	0.0030	0.0181	0.0000	0.0003	0.0013	0.0011	0.0015
	Bioharvest Recovery	0.0341	-0.1490	0.0002	0.0015	0.0054	0.0041	0.0044
	Pellet Plant	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Power Plant	0.0096	0.2479	0.0000	0.0129	0.0138	0.0000	-0.0002
	LCA Total	0.0468	0.1176	0.0002	0.0147	0.0206	0.0052	0.0059
	Forest Carbon (avg. 100 years)	0.3557						
Total		**0.4025**	**0.1176**	**0.0002**	**0.0147**	**0.0206**	**0.0052**	**0.0059**

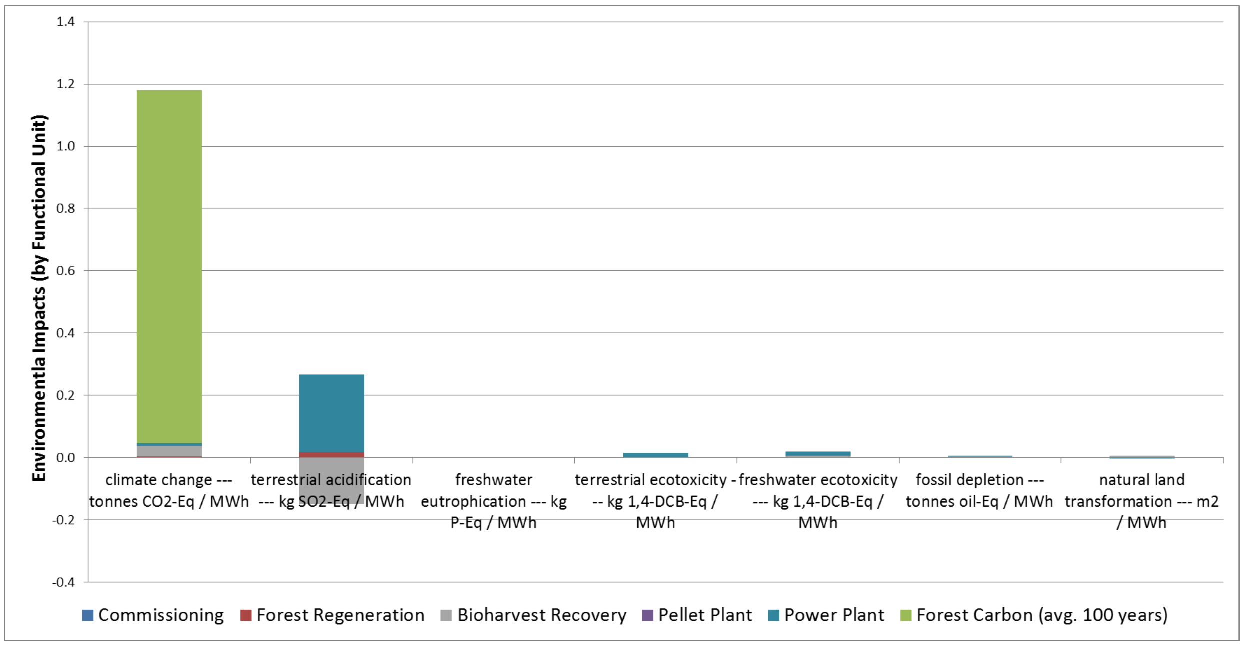


Figure 71. Environmental Impacts – bioenergy scenario F

Appendix E. GHG emission profiles for bioenergy scenarios – Details

E.1. Bioenergy scenario B

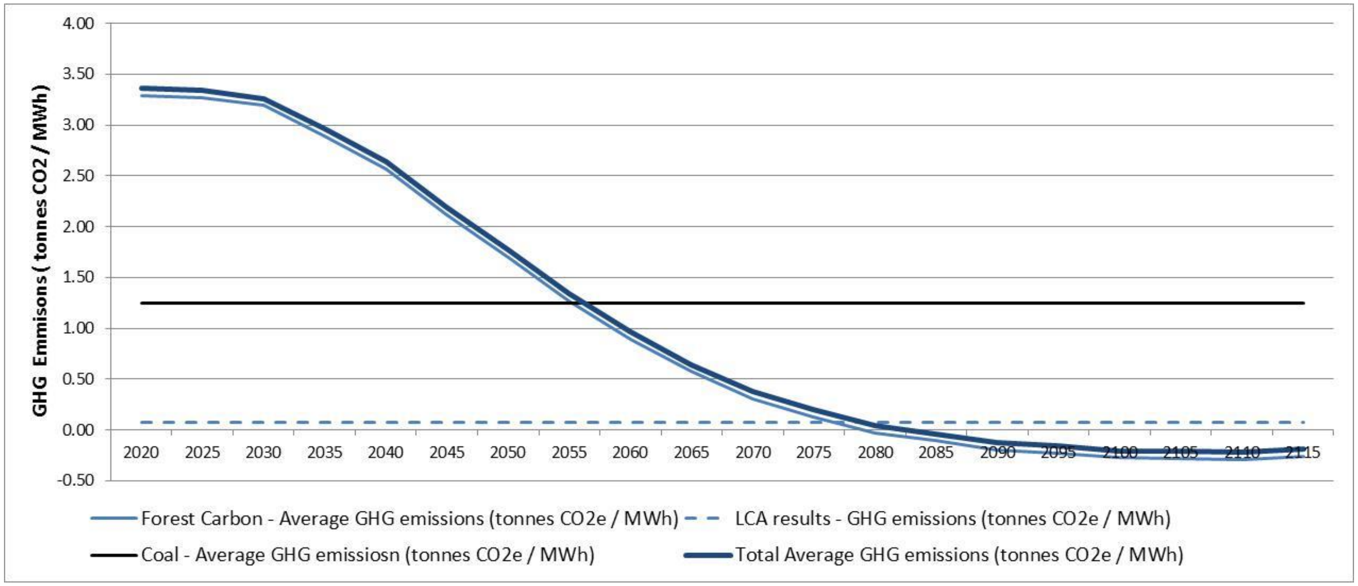


Figure 72. Bioenergy scenario B – Normalized GHG emissions

Forest Carbon GHG emissions combined with LCA GHG emissions (CO_2e / MWh)

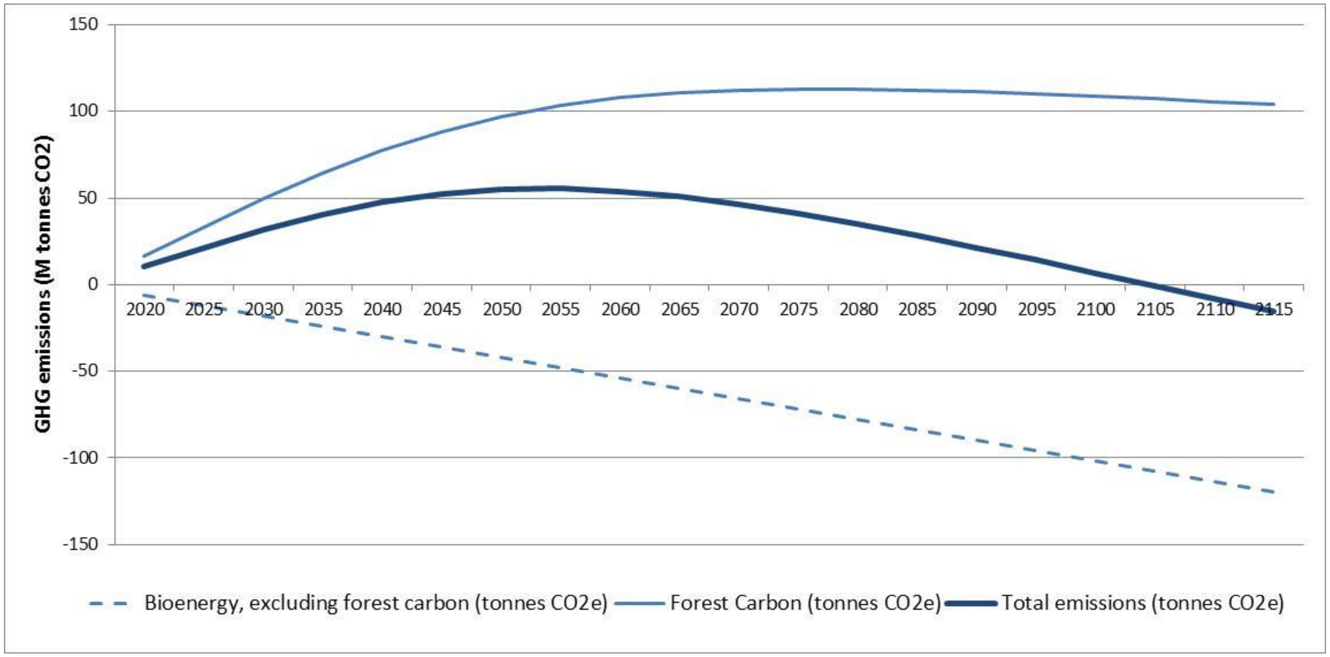


Figure 73. Bioenergy scenario B – Cumulative GHG emissions

E.2. Bioenergy scenario D

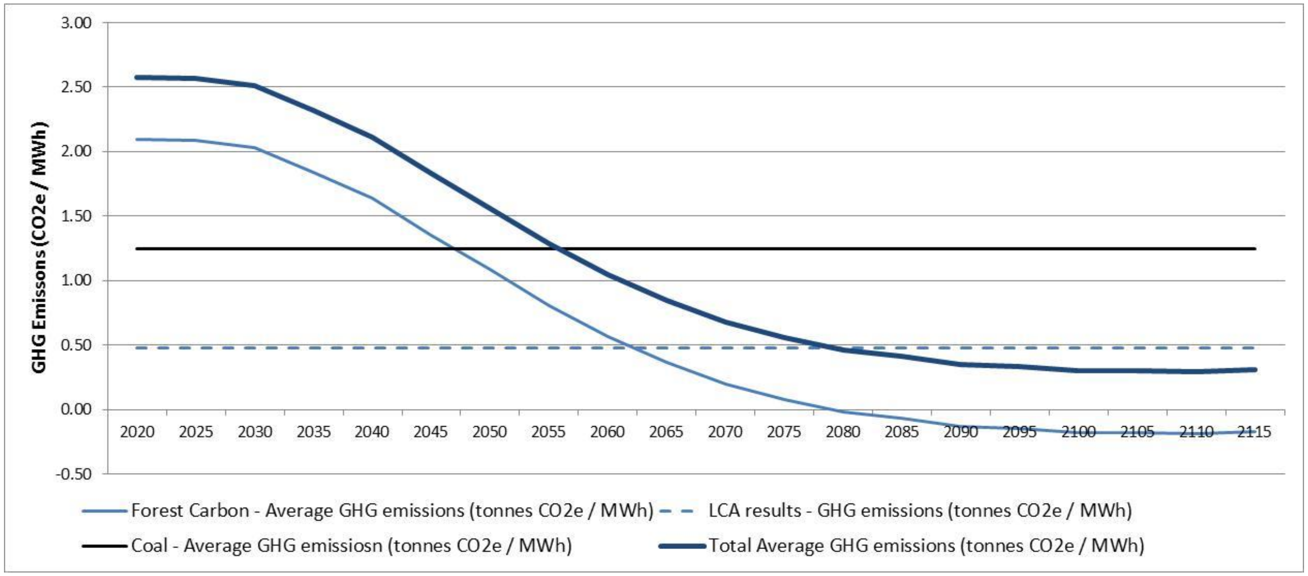


Figure 74. Bioenergy scenario D – Normalized GHG emissions
Forest Carbon GHG emissions combined with LCA GHG emissions (CO_2e / MWh)

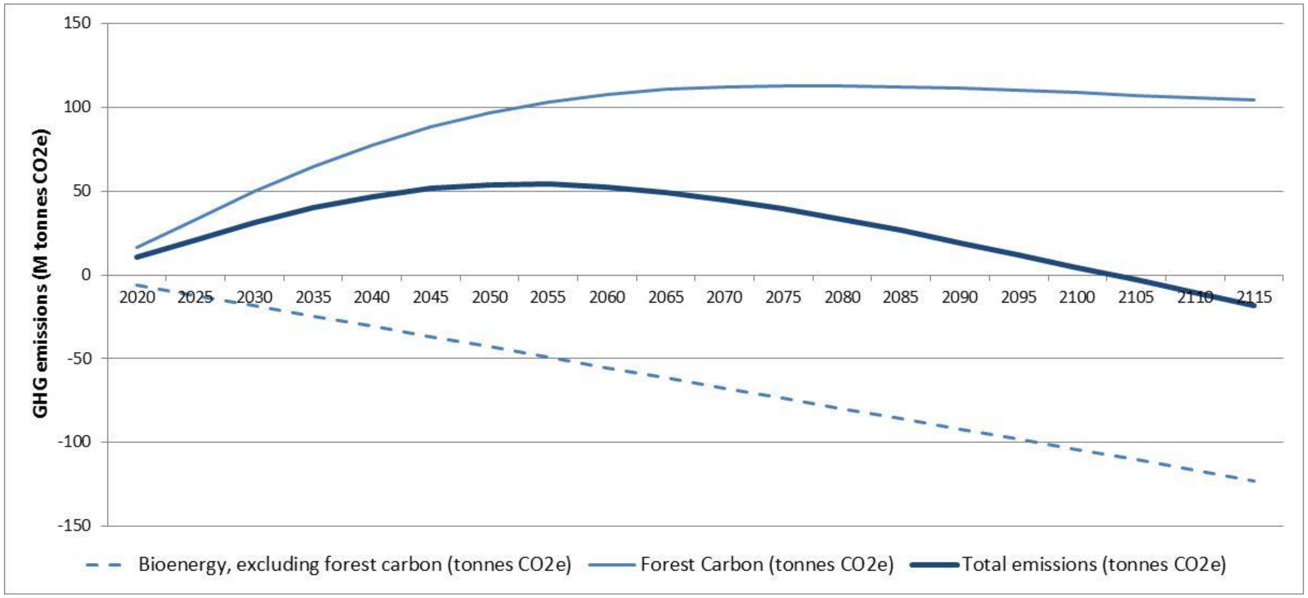


Figure 75. Bioenergy scenario D – Cumulative GHG emissions

E.3. Bioenergy scenario F

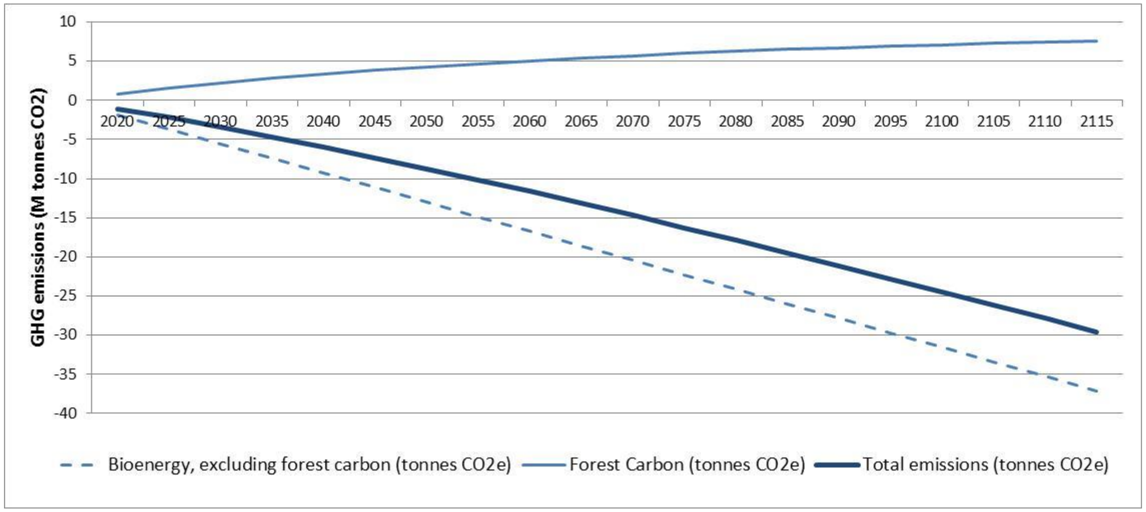


Figure 76. Bioenergy scenario F – Normalized GHG emissions

Forest Carbon GHG emissions combined with LCA GHG emissions (CO_2e / MWh)

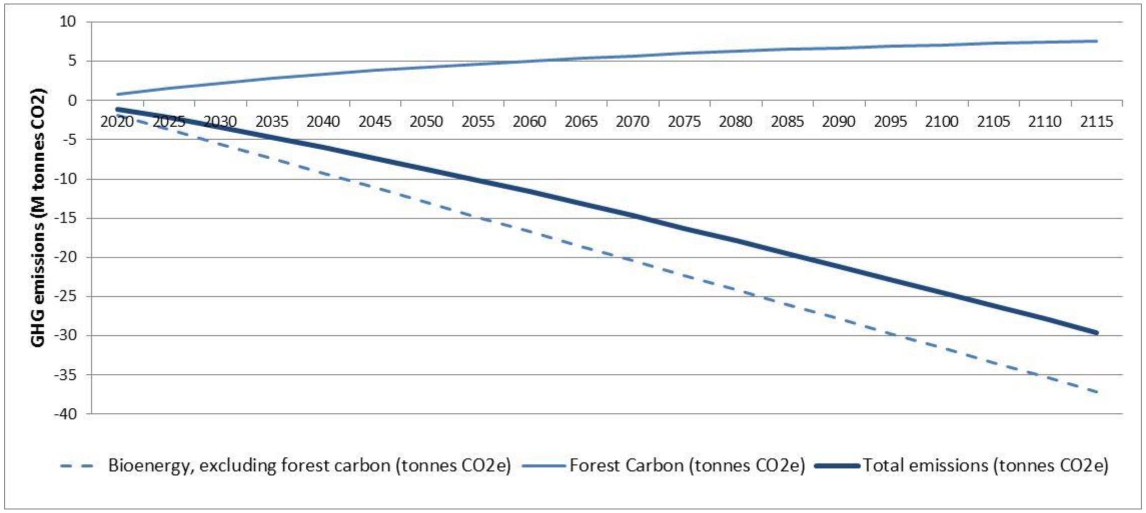


Figure 77. Bioenergy scenario F – Cumulative GHG emissions

Appendix F. Main Project Assumptions

Table 64. Main Project Assumptions

Project Assumption
Forestry
The increase in harvesting of unmerchantable hardwood species drives the harvesting of incidental softwood. Therefore, the environmental impacts of harvesting the softwood species are included in the analysis and attributed to the bioenergy scenarios
Trading of softwood for hardwood. This incidental softwood harvest is traded for an equal amount of hardwood from the pulp and paper industry. There is enough hardwood available to trade under the BH0 biofibre harvest scenario. This trading is 1-to-1
Harvest levels and % utilization is constant throughout the planning horizon for BH0, BH2 and BH3
The amount of available biofibre defined by FPInnovations is available and constant year to year over the 100-year planning horizon
Future stands for harvest would have attributes similar to the stands identified in the 4 FMU FMPs
Harvest of red and white pine was avoided
An average of 2% of all stands were retained in cutblocks in order to simulate the retention of 25 well-spaced trees/ha requirement
For full-tree harvesting, 30% of unmerchantable biofibre was left in the cutblock. For DDC harvesting, 25% of unmerchantable biofibre was left in the cutblock
For BH2 and BH3, the road-side slash amounts defined in BH0 are once again burned at the same rate
For BH0 and BH1, 831 km of new main forestry roads were needed to satisfy the 10-year harvest plan. Road width is 10m.

The construction of main forestry roads will decline by 1% / year through to the end of the planning horizon. No new main forestry roads were required for BH2 and BH3. For BH2, 371 km / year of in-block (tertiary roads) were required to access additional biofibre in the new cutblocks. Road width is 5m. For BH3, 734 km / year of in-block (tertiary roads) were required to access additional biofibre in new cutblocks. Road width is 5m.
Carbon modelling
Carbon neutrality is not assumed and the carbon accounting framework used includes the effects of biofibre harvesting on the forests
85% of the carbon contained in road-side slash is burned with a very small percentage being converted to black carbon
The remaining 15% of carbon in slash piles does not burn, and this carbon decays at a defined rate
When converting forest carbon results to GHG emissions, the carbon is converted to CO2 using a conversion factor of 3.6667 (44/12)
For BH2 and BH3, additional road-side slash is not burned and is left to decompose
Dry biofibre contains 50% carbon by weight
32% of road-side slash is burned
Landscape-level
New main roads are permanent.
Natural disturbance perturbation rates will be limited to wildfire and endemic insect/disease damage.
Tertiary roads for BH2 and BH3 have a lifespan of 20 years at which point natural forest regeneration reclaims these features from the landscape and the roads no longer contribute to fragmentation.
Edges from cutblocks and burned areas persist for 20 years following harvest at which point successful regeneration has eliminated perceptible stand edge
Cogen
For the "modified" cogen, electricity is generated at 23.7% efficiency and the residual heat was assumed to generate

electricity at 25%.

Appendix G. Pedigree Matrix Scores

Table 65. Pedigree matrix score (climate change)

Life Cycle Stage	Emission Factor Source	Activity Data Source	Temporal Representation (1-5)	Geographical Representation (1-5)	Technology Representation (1-5)	Activity Data Certainty (1-5)	Score
Biomass							
Clear land for forestry roads	FP Innovations	FP Innovations	5	5	5	3	4.5
Extract gravel for forestry roads	Ecoinvent	Silvatech	2	2	3	3	2.5
Retrofit Atikokan station	Ecoinvent	Econ. alloc.	1	2	5	3	2.8
Construct pellet plants	Ecoinvent	n/a	3	2	5	3	3.3
Construct cogen plant	Ecoinvent	n/a	2	2	3	5	3.0
Aerial spray	FP Innovations	FP Innovations	5	5	5	3	4.5
Forest camps	FP Innovations	FP Innovations	5	5	5	3	4.5
Recover biomass	FP Innovations	FP Innovations	5	5	5	3	4.5
Debark trees	FP Innovations	FP Innovations	5	5	5	3	4.5
Chip biomass (wood and slash)	FP Innovations	FP Innovations	5	5	5	3	4.5
Transport biomass	FP Innovations	FP Innovations	5	5	5	3	4.5
Burn slash piles	SEI	OMNR	5	3	5	3	4.0
Pellet plant inventory control	Ecoinvent	McKechnie	2	2	3	5	3.0
Debark logs	NIR/NPRI	McKechnie	5	5	5	5	5.0
Dry biofibre	Envirochem	McKechnie	5	5	1	5	4.0
Press Pellets	NIR/NPRI	McKechnie	5	5	5	5	5.0
Transport pellets	Ecoinvent	McKechnie	3	2	3	5	3.3
Transport ash (pellet plant)	Ecoinvent	McKechnie	3	2	3	5	3.3
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Combust pellets for power	Envirochem	McKechnie	5	5	1	5	4.0
Combust hog fuel in cogen	Envirochem	McKechnie	5	5	1	5	4.0
Dispose wood ash (power plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Coal							
Construct coal power plant	Ecoinvent	n/a	1	2	5	5	3.3
Extract coal	Coal SP	McKechnie	5	5	5	5	5.0
Transport coal to Atikokan	Ecoinvent	McKechnie	2	3	5	5	3.8
Combust coal	NPRI	McKechnie	5	5	5	5	5.0
Dispose coal ash	Ecoinvent	McKechnie	1	2	3	5	2.8

Table 66. Pedigree matrix score (terrestrial acidification)

Life Cycle Stage (terrestrial acidification)	Emission Factor Source	Activity Data Source	Temporal Representation (1-5)	Geographical Representation (1-5)	Technology Representation (1-5)	Activity Data Certainty (1-5)	Score
Biomass							
Clear land for forestry roads	Ecoinvent	Silvatech	3	2	3	3	2.8
Extract gravel for forestry roads	Ecoinvent	Silvatech	2	2	3	3	2.5
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	1	2	5	3	2.8
Construct pellet plants	Ecoinvent	n/a	3	2	5	3	3.3
Construct cogen plant	Ecoinvent	n/a	2	2	3	5	3.0
Aerial spray	Ecoinvent	Assumption	2	2	3	1	2.0
Forest camps	Ecoinvent	Assumption	2	2	5	1	2.5
Recover biomass	Ecoinvent	Estimated	2	2	3	3	2.5
Debark trees	Ecoinvent	Estimated	2	2	3	3	2.5
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	2	2	5	3	3.0
Transport biomass	Ecoinvent	FP Innovations	4	2	3	3	3.0
Burn slash piles	SEI	OMNR	5	3	5	3	4.0
Pellet plant inventory control	Ecoinvent	McKechnie	2	2	5	5	3.5
Debark logs	NPRI	McKechnie	5	5	5	5	5.0
Dry biofibre	Envirochem	McKechnie	5	5	1	5	4.0
Press Pellets	NPRI	McKechnie	5	5	5	5	5.0
Transport pellets	Ecoinvent	McKechnie	3	2	3	5	3.3
Transport ash (pellet plant)	Ecoinvent	McKechnie	3	2	3	5	3.3
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Combust pellets for power	Envirochem	McKechnie	5	5	1	5	4.0
Combust hog fuel in cogen	Envirochem	McKechnie	5	5	1	5	4.0
Dispose wood ash (power plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Coal							
Construct coal power plant	Ecoinvent	n/a	1	2	5	5	3.3
Extract coal	Coal SP	McKechnie	5	5	5	5	5.0
Transport coal to Atikokan	Ecoinvent	McKechnie	2	3	5	5	3.8
Combust coal	NPRI	McKechnie	5	5	5	5	5.0
Dispose coal ash	Ecoinvent	McKechnie	1	2	3	5	2.8

Table 67. Pedigree matrix score (freshwater eutrophication)

Life Cycle Stage (freshwater eutrophication)	Emission Factor Source	Activity Data Source	Temporal Representation (1-5)	Geographical Representation (1-5)	Technology Representation (1-5)	Activity Data Certainty (1-5)	Score
Biomass							
Clear land for forestry roads	Ecoinvent	Silvatech	3	2	3	3	2.8
Extract gravel for forestry roads	Ecoinvent	Silvatech	2	2	3	3	2.5
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	1	2	5	3	2.8
Construct pellet plants	Ecoinvent	n/a	3	2	5	3	3.3
Construct cogen plant	Ecoinvent	n/a	2	2	3	5	3.0
Aerial spray	Ecoinvent	Assumption	2	2	3	1	2.0
Forest camps	Ecoinvent	Assumption	2	2	5	1	2.5
Recover biomass	Ecoinvent	Estimated	2	2	3	3	2.5
Debark trees	Ecoinvent	Estimated	2	2	3	3	2.5
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	2	2	5	3	3.0
Transport biomass	Ecoinvent	FP Innovations	4	2	3	3	3.0
Burn slash piles	Data gap	Data gap	Data gap	Data gap	Data gap	Data gap	n/a
Pellet plant inventory control	Ecoinvent	McKechnie	2	2	5	5	3.5
Debark logs	Ecoinvent	McKechnie	1	2	1	5	2.3
Dry biofibre	Ecoinvent	McKechnie	1	2	3	5	2.8
Press Pellets	Ecoinvent	McKechnie	1	2	1	5	2.3
Transport pellets	Ecoinvent	McKechnie	3	2	3	5	3.3
Transport ash (pellet plant)	Ecoinvent	McKechnie	3	2	3	5	3.3
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Combust pellets for power	Ecoinvent	McKechnie	2	2	3	5	3.0
Combust hog fuel in cogen	Ecoinvent	McKechnie	2	2	3	5	3.0
Dispose wood ash (power plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Coal							
Construct coal power plant	Ecoinvent	n/a	1	2	5	5	3.3
Extract coal	Ecoinvent	McKechnie	1	2	3	5	2.8
Transport coal to Atikokan	Ecoinvent	McKechnie	2	3	5	5	3.8
Combust coal	Ecoinvent	McKechnie	1	2	3	5	2.8
Dispose coal ash	Ecoinvent	McKechnie	1	2	3	5	2.8

Table 68. Pedigree matrix score (terrestrial ecotoxicity)

Life Cycle Stage (terrestrial ecotoxicity)	Emission Factor Source	Activity Data Source	Temporal Representation (1-5)	Geographical Representation (1-5)	Technology Representation (1-5)	Activity Data Certainty (1-5)	Score
Biomass							
Clear land for forestry roads	Ecoinvent	Silvatech	3	2	3	3	2.8
Extract gravel for forestry roads	Ecoinvent	Silvatech	2	2	3	3	2.5
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	1	2	5	3	2.8
Construct pellet plants	Ecoinvent	n/a	3	2	5	3	3.3
Construct cogen plant	Ecoinvent	n/a	2	2	3	5	3.0
Aerial spray	Ecoinvent	Assumption	2	2	3	1	2.0
Forest camps	Ecoinvent	Assumption	2	2	5	1	2.5
Recover biomass	Ecoinvent	Estimated	2	2	3	3	2.5
Debark trees	Ecoinvent	Estimated	2	2	3	3	2.5
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	2	2	5	3	3.0
Transport biomass	Ecoinvent	FP Innovations	4	2	3	3	3.0
Burn slash piles	Data gap	Data gap	Data gap	Data gap	Data gap	Data gap	n/a
Pellet plant inventory control	Ecoinvent	McKechnie	2	2	5	5	3.5
Debark logs	NPRI-Ecoinvent	McKechnie	3	3.5	3	5	3.6
Dry biofibre	Ecoinvent	McKechnie	1	2	3	5	2.8
Press Pellets	NPRI-Ecoinvent	McKechnie	3	3.5	3	5	3.6
Transport pellets	Ecoinvent	McKechnie	3	2	3	5	3.3
Transport ash (pellet plant)	Ecoinvent	McKechnie	3	2	3	5	3.3
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Combust pellets for power	Ecoinvent	McKechnie	2	2	3	5	3.0
Combust hog fuel in cogen	Ecoinvent	McKechnie	2	2	3	5	3.0
Dispose wood ash (power plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Coal							
Construct coal power plant	Ecoinvent	n/a	1	2	5	5	3.3
Extract coal	Ecoinvent	McKechnie	1	2	3	5	2.8
Transport coal to Atikokan	Ecoinvent	McKechnie	2	3	5	5	3.8
Combust coal	NPRI-Ecoinvent	McKechnie	3	3.5	4	5	3.9
Dispose coal ash	Ecoinvent	McKechnie	1	2	3	5	2.8

Table 69. Pedigree matrix score (freshwater ecotoxicity)

Life Cycle Stage (freshwater ecotoxicity)	Emission Factor Source	Activity Data Source	Temporal Representation (1-5)	Geographical Representation (1-5)	Technology Representation (1-5)	Activity Data Certainty (1-5)	Score
Biomass							
Clear land for forestry roads	Ecoinvent	Silvatech	3	2	3	3	2.8
Extract gravel for forestry roads	Ecoinvent	Silvatech	2	2	3	3	2.5
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	1	2	5	3	2.8
Construct pellet plants	Ecoinvent	n/a	3	2	5	3	3.3
Construct cogen plant	Ecoinvent	n/a	2	2	3	5	3.0
Aerial spray	Ecoinvent	Assumption	2	2	3	1	2.0
Forest camps	Ecoinvent	Assumption	2	2	5	1	2.5
Recover biomass	Ecoinvent	Estimated	2	2	3	3	2.5
Debark trees	Ecoinvent	Estimated	2	2	3	3	2.5
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	2	2	5	3	3.0
Transport biomass	Ecoinvent	FP Innovations	4	2	3	3	3.0
Burn slash piles	Data gap	Data gap	Data gap	Data gap	Data gap	Data gap	n/a
Pellet plant inventory control	Ecoinvent	McKechnie	2	2	5	5	3.5
Debark logs	Ecoinvent-NPRI	McKechnie	3	3.5	3	5	3.6
Dry biofibre	Ecoinvent	McKechnie	1	2	3	5	2.8
Press Pellets	Ecoinvent-NPRI	McKechnie	3	3.5	3	5	3.6
Transport pellets	Ecoinvent	McKechnie	3	2	3	5	3.3
Transport ash (pellet plant)	Ecoinvent	McKechnie	3	2	3	5	3.3
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Combust pellets for power	Ecoinvent	McKechnie	2	2	3	5	3.0
Combust hog fuel in cogen	Ecoinvent	McKechnie	2	2	3	5	3.0
Dispose wood ash (power plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Coal							
Construct coal power plant	Ecoinvent	n/a	1	2	5	5	3.3
Extract coal	Ecoinvent	McKechnie	1	2	3	5	2.8
Transport coal to Atikokan	Ecoinvent	McKechnie	2	3	5	5	3.8
Combust coal	Ecoinvent-NPRI	McKechnie	3	3.5	4	5	3.9
Dispose coal ash	Ecoinvent	McKechnie	1	2	3	5	2.8

Table 70. Pedigree matrix score (natural land transformation)

Life Cycle Stage (land transformation)	Emission Factor Source	Activity Data Source	Temporal Representation (1-5)	Geographical Representation (1-5)	Technology Representation (1-5)	Activity Data Certainty (1-5)	Score
Biomass							
Clear land for forestry roads	Ecoinvent	Silvatech	3	2	3	3	2.8
Extract gravel for forestry roads	Ecoinvent	Silvatech	2	2	3	3	2.5
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	1	2	5	3	2.8
Construct pellet plants	Ecoinvent	n/a	3	2	5	3	3.3
Construct cogen plant	Ecoinvent	n/a	2	2	3	5	3.0
Aerial spray	Ecoinvent	Assumption	2	2	3	1	2.0
Forest camps	Ecoinvent	Assumption	2	2	5	1	2.5
Recover biomass	Ecoinvent	Estimated	2	2	3	3	2.5
Debark trees	Ecoinvent	Estimated	2	2	3	3	2.5
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	2	2	5	3	3.0
Transport biomass	Ecoinvent	FP Innovations	4	2	3	3	3.0
Burn slash piles	Data gap	Data gap	Data gap	Data gap	Data gap	Data gap	n/a
Pellet plant inventory control	Ecoinvent	McKechnie	2	2	5	5	3.5
Debark logs	Ecoinvent	McKechnie	1	2	1	5	2.3
Dry biofibre	Ecoinvent	McKechnie	1	2	3	5	2.8
Press Pellets	Ecoinvent	McKechnie	1	2	1	5	2.3
Transport pellets	Ecoinvent	McKechnie	3	2	3	5	3.3
Transport ash (pellet plant)	Ecoinvent	McKechnie	3	2	3	5	3.3
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Combust pellets for power	Ecoinvent	McKechnie	2	2	3	5	3.0
Combust hog fuel in cogen	Ecoinvent	McKechnie	2	2	3	5	3.0
Dispose wood ash (power plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Coal							
Construct coal power plant	Ecoinvent	n/a	1	2	5	5	3.3
Extract coal	Ecoinvent	McKechnie	1	2	3	5	2.8
Transport coal to Atikokan	Ecoinvent	McKechnie	2	3	5	5	3.8
Combust coal	Ecoinvent	McKechnie	1	2	3	5	2.8
Dispose coal ash	Ecoinvent	McKechnie	1	2	3	5	2.8

Table 71. Pedigree matrix score (fossil fuel depletion)

Life Cycle Stage (fossil fuel depletion)	Emission Factor Source	Activity Data Source	Temporal Representation (1-5)	Geographical Representation (1-5)	Technology Representation (1-5)	Activity Data Certainty (1-5)	Score
Biomass							
Clear land for forestry roads	Ecoinvent	Silvatech	3	2	3	3	2.8
Extract gravel for forestry roads	Ecoinvent	Silvatech	2	2	3	3	2.5
Retrofit Atikokan station	Ecoinvent	Econ. Alloc.	1	2	5	3	2.8
Construct pellet plants	Ecoinvent	n/a	3	2	5	3	3.3
Construct cogen plant	Ecoinvent	n/a	2	2	3	5	3.0
Aerial spray	Ecoinvent	Assumption	2	2	3	1	2.0
Forest camps	Ecoinvent	Assumption	2	2	5	1	2.5
Recover biomass	Ecoinvent	Estimated	2	2	3	3	2.5
Debark trees	Ecoinvent	Estimated	2	2	3	3	2.5
Chip biomass (wood and slash)	Ecoinvent	FP Innovations	2	2	5	3	3.0
Transport biomass	Ecoinvent	FP Innovations	4	2	3	3	3.0
Burn slash piles	Data gap	Data gap	Data gap	Data gap	Data gap	Data gap	n/a
Pellet plant inventory control	Ecoinvent	McKechnie	2	2	5	5	3.5
Debark logs	Ecoinvent	McKechnie	1	2	1	5	2.3
Dry biofibre	Ecoinvent	McKechnie	1	2	3	5	2.8
Press Pellets	Ecoinvent	McKechnie	1	2	1	5	2.3
Transport pellets	Ecoinvent	McKechnie	3	2	3	5	3.3
Transport ash (pellet plant)	Ecoinvent	McKechnie	3	2	3	5	3.3
Dispose wood ash (pellet plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Combust pellets for power	Ecoinvent	McKechnie	2	2	3	5	3.0
Combust hog fuel in cogen	Ecoinvent	McKechnie	2	2	3	5	3.0
Dispose wood ash (power plant)	Ecoinvent	McKechnie	1	2	3	5	2.8
Coal							
Construct coal power plant	Ecoinvent	n/a	1	2	5	5	3.3
Extract coal	Ecoinvent	McKechnie	1	2	3	5	2.8
Transport coal to Atikokan	Ecoinvent	McKechnie	2	3	5	5	3.8
Combust coal	Ecoinvent	McKechnie	1	2	3	5	2.8
Dispose coal ash	Ecoinvent	McKechnie	1	2	3	5	2.8

Appendix H. Ecoinvent processes

Table 72. Ecoinvent processes used and adjustments to specific factors

Activity Label	Ecoinvent Process	Proxying Description	Adjusted Data
Clear land for forestry roads	round wood, primary forest, clear-cutting, at forest road	No proxying	No proxying
Extract gravel for forestry roads	gravel, round, at mine	No proxying	No proxying
Retrofit Atikokan station	lignite power plant	Adjusted the lignite power plant construction process using economic allocation (25%).	Multiplied Ecoinvent factors by 25%
Construct pellet plant infrastructure - furnace	furnace, pellets, 50kW	No proxying	No proxying
Construct pellet plant infrastructure - pellet press	wood pellet manufacturing, infrastructure	No proxying	No proxying
Construct pellet plant infrastructure - drying kiln	technical wood drying, infrastructure	No proxying	No proxying
Construct cogen plant	cogen unit 6400kWth, wood burning, building	No proxying	No proxying
Construct coal power plant	lignite power plant	No proxying	No proxying
Generate Ontario Grid Electricity	proxy of electricity, low voltage, at grid,	Several emissions from Ecoinvent replaced by NPRI values for Ontario grid	EC NIR: GHGs NPRI: SO2, Nox, NH3, phosphorus, Arsenic, benzene, cadmium, chromium, cobalt, copper, formaldehyde, lead, manganese, mercury, nickel, phenol, toluene, vanadium, xylene, zinc
Extract coal	lignite, at mine	Several factors replaced with NREL and coal subproject research	Coal sub-project: GHGs, Nox, SO2, cadmium, dioxins/furans, lead, mercury NREL: Manganese (water)
Transport coal to Atikokan	transport, freight, rail, diesel	No proxying	No proxying
Aerial spray (herbicide)	transport, aircraft, freight	No proxying	No proxying

Field diesel equipment (includes diesel generators at forest camp)	diesel, burned in building machine	Several factors replaced by NREL	NREL: CO2, CH4, Nox, SO2, acetylaldehyde, acrolein, benzene, formaldehyde, PAH, toluene, xylene
Recover roundwood to forest road (includes skidding and delimbing)	round wood, hardwood, under bark, u=70%, at forest road	Ecoinvent subprocesses not applicable to the project have been removed. Fuel and electricity emissions (where applicable) adjusted with specific data. Adjustments made for the difference in functional units between Ecoinvent and project.	FP Innovations: GHGs
Recover slash to forest road (includes skidding and delimbing)	residual wood, hardwood, under bark, u=80%, at forest road		FP Innovations: GHGs
Debark trees	round wood, softwood, debarked, u=70% at forest road - use as proxy for hardwood		FP Innovations: GHGs
Chip biomass (roundwood and slash)	wood chopping, mobile chopper, in forest		FP Innovations: GHGs
Transport biomass	transport, lorry >32t, EURO5	No proxying	No proxying
Burn slash piles	Ecoinvent did not have a suitable process to use		SEI (2010): CH4, N2O Oneil et al: Nox, SO2 All other environmental releases zeroed out including CO2 (included in forest carbon modelling).
Pellet plant inventory control	diesel, burned in building machine	No proxying	No proxying
Debark logs	see above for Ontario grid		
Dry biofibre	sawn timber, hardwood, raw, kiln dried, u=10%, at plant	Converted functional unit to per unit input heating fuel	Envirochem: CH4, N2O, Nox, SO2, cadmium, lead, mercury, PAH
Press Pellets	see above for Ontario grid		
Transport pellets	transport, lorry >32t, EURO5	No proxying	No proxying

Transport ash (pellet plant)	transport, lorry >32t, EURO5	No proxying	No proxying
Dispose wood ash (pellet plant)	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	No proxying	No proxying
Combust pellets at Atikokan	pellets, mixed, burned in furnace 50kW	Ecoinvent subprocesses not applicable to the project have been removed. Specific factors have been proxied using Envirochem data	Envirochem: Nox, SO2, cadmium, chlorine, lead, mercury, PAH McKechnie: Plant efficiency
Combust coal	electricity, lignite, at power plant	Proxied using NPRI data for Atikokan station	NPRI: GHGs, Nox, SO2, arsenic, cadmium, dioxins/furans, lead, mercury, phosphorus
Combust hog fuel in cogen	pellets, mixed, burned in furnace 50kW	Ecoinvent subprocesses not applicable to the project have been removed. Specific factors have been proxied using Envirochem data	Envirochem: Nox, SO2, cadmium, chlorine, lead, mercury, PAH McKechnie: Plant efficiency
Dispose coal ash	disposal, hard coal ash, 0% water, to residual material landfill	No proxying	No proxying
Dispose wood ash (power plant)	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	No proxying	No proxying

Appendix I. Modified Cogen Description

Total system efficiency calculation for CHP systems is one of the two efficiency calculations recommended by EPA and accepted and used by the energy industry at large. In this calculation, however, the value of the power output and the thermal output is not differentiated; instead power output and thermal output are treated as additive properties with the same relative value.

$$\eta_o = \frac{W_E + \Sigma Q_{th}}{Q_{fuel}}$$

η_o : total system efficiency

W_E : net useful power output

ΣQ_{TH} : sum of the net useful thermal outputs

Q_{FUEL} : total fuel input

In reality and practice, thermal output and power output are not interchangeable.

In an effort not to penalize a typical CHP application that must meet concurrent needs of power and thermal demands while putting a value to the thermal output of a CHP system which could have been used to generate electricity, the following estimation methodology is developed and used in allocation calculations:

Assuming a typical conversion efficiency of biomass to electricity of about 25%, an equivalent power output from the net thermal output of a CHP system can be estimated by multiplying the net useful thermal energy production (in MWh) by 0.25. A total power equivalency (MWh) that could hypothetically be produced in a CHP system could then be estimated as follows:

Hypothetical MWh output (in power equivalence) = MWh electrical output + MWh thermal output*0.25

Appendix J. Critical review summary