Milestone 3 – Final Report

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Milestone 3: Methodology for Low Carbon Fuel Pathways and Default Carbon Intensities

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Glossary

General Terminology	
Background and supporting unit processes:	Materials and energy used as part of a pathway including fertilizers, chemicals, regional grid electricity, etc. These unit processes will be available in the tool for viewing and use in new pathways.
Baseline pathway	Canadian diesel and gasoline pathways which the Clean Fuel Standard uses for reference carbon intensities. These pathways are built into the Fuel LCA Modeling tool and used for companionate analysis.
By-product	By-products generally do not have economic value and are treated as wastes.
Characterization factor	A scalar quantity, or weighting factor, indicating the greenhouse gas potential (or Global Warming Potential, GWP) of an emission. A general term that may also refer to scale factors associated with other potential impacts.
Co-product	A product which is created from any production or agricultural process, including silviculture, aquaculture, etc., which is not the prime economic driver of the activity. It can be any of two or more products coming from the same unit process or product system. Examples include corn cobs and husks (stover) co-produced with corn, glycerin which is produced as a co-product of biodiesel esterification, and animal fodder (feed) produced concurrently with the fermentation of ethanol and other alcohols.
Database	A repository in the tool which collects pathways, background and supporting unit processes, characterization factors, pathway metadata, user metadata and other information as needed.
Library	A set of information in the database available to all users but editable only by ECCC and/or its subcontractors. Includes pathways and other unit processes and the characterization factors, etc.
Metadata	Information on a pathway or user which is useful in providing transparency, traceability, verifiability, and/or aids in carbon intensity calculations.
Method	A specific set of characterization factors
Monte Carlo Analysis	An assessment of uncertainty created by running a calculation over and over again (typically more than 1000 times) while varying the underlying uncertainty differently each time.
New low carbon pathway	A pathway created by a tool user.
Waste	Substances or objects with no economic value for which the holder intends or is required to dispose of
Fuel production-specific terminology	
%wt	Percentage on a weight basis
CHP	Combined Heat and Power
CI	Carbon Intensity
CNG	Compressed Natural Gas
GHG	Greenhouse Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model
HFO	Heavy Fuel Oil
HHV	High Heating Value
IPCC AR5	Intergovernmental Panel on Climate Change 5th Assessment Report
LCA	Life Cycle Assessment
LFO	Light Fuel Oil
LHV	Low Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MSW	Municipal solid waste
NG	Natural Gas

NGL	Natural Gas Liquids
RNG	Renewable natural gas
RU	Regional Unit
SOC	Soil organic Carbon
UCO	Used cooking oil
WWT	Wastewater treatment

Units

Unit	Description	Conversions
bbl.km	Barrel-kilometer	0.16 m^3.km
Wh	Watt-hour	0.0036 MJ
kWh	Kilo watt-hours	1,000 Wh
MWh	Mega watt-hours	1,000,000 Wh
btu	British thermal unit	0.001056 MJ
kg	Kilogram	1,000 g
km	Kilometer	1,000 m
mile	mile	1609.35 m
t	Tonne or ton	1,000,000 g
tkm	Tonne-kilometer	1,000 kg.km
MJ	Megajoule	1,000,000 J
l	Liter	0.001 m^3

1. Introduction

The Government of Canada has announced its intent to develop a Clean Fuel Standard (CFS) to reduce Canada's greenhouse gas (GHG) emissions through the increased use of lower carbon fuels and alternative technologies. The objective of the CFS is to achieve 30 megatons of annual reductions in GHG emissions by 2030, contributing to Canada's effort to achieve its overall GHG mitigation target of 30% emissions reduction below 2005 levels by 2030. To achieve this goal, fossil fuel suppliers (e.g., refiners, natural gas distributors) will be required to reduce the carbon intensity of the fuels they produce or distribute for use in Canada's transportation, industry, and building sectors. The carbon intensity of a fuel is a representation of the total life cycle GHG emissions (expressed in kg of CO_2 equivalents) associated with production of 1 MJ of energy from that fuel, including feedstock extraction and processing, fuel production and upgrading, transport and distribution throughout the life cycle, and combustion of the fuel. Under the CFS, baseline carbon intensity values will be set for fossil fuels covered by the regulations based on the 2016 average carbon intensity of these fuels. These baselines will be used to establish the carbon intensity targets or requirements that fuel producers will have to meet for the fuels they supply. The carbon intensity requirements will be expressed as an absolute value set at a level lower than the baseline. These carbon intensity requirements will become more stringent over time. Non-fossil fuel producers, referred to as low carbon fuel producers, will not have their fuel production regulated by the CFS; however, low carbon fuel producers will be eligible to generate credits by supplying fuels that have lower life cycle carbon intensities than the reference fossil fuel they would displace (ECCC, 2018).

The Fuel LCA Modeling Tool will be used to set baseline carbon intensity values for fossil fuel producers, as well as serve as a tool for low carbon fuel producers to submit the life cycle carbon intensities of their fuels for potential credit generation under the CFS (ECCC 2018a).

In October of 2018, ECCC commissioned EarthShift Global, WSP and Quinn & Partners, and Introspective Systems to develop a robust, user-friendly, and transparent software tool that is compliant with the ISO 14040 and 14044 LCA standards (ISO, 2006a) (ISO, 2006b) and contains Canadian-specific fuel pathway data. This tool will be used to calculate the carbon intensity of existing and future Canadian fossil fuel and low carbon fuel pathways in support of the CFS policy and regulations. The project to develop the CFS carbon intensity software tool is comprised of four stages or milestones, including:

- Milestone 1 – Development of the Conceptual Model (completed Jan 31, 2019);
- Milestone 2 – Methodology for Fossil Fuel Pathways and Baseline Carbon Intensities (completed May 15, 2019);
- Milestone 3 – Methodology for Low Carbon Fuel Pathways and Default Carbon Intensities (to be completed by August 15, 2019); and
- Milestone 4 – Development of the Fuel LCA Modeling Tool and Documentation (to be completed by March 13, 2020).

Milestone 3 sets the model building blocks and foundational carbon intensities for low carbon fuels under the CFS and is an important foundation for upcoming policy on clean fuels. Wherever possible, published LCAs and LCA models relating to the Canadian situation have been used as a basis for the pathway models. Where unit process models were not available, preference was given to published Canadian or North American data. In some cases, other GHG tools or US data have been used. Areas where additional time and/or research could refine the values used in the baseline have been noted as recommendations for future work.

This report summarizes the work completed for Milestone 3, Task 3.3: A final report of the methodology and data sources as well as the carbon intensity values for the low carbon fuel pathways. This report has been prepared to address the relevant reporting requirements for a comparative LCA under the ISO 14044 guidelines.

Part I: General Methods and Approach

2. Goal and Scope Definition

According to ISO 14044, the first phase of an LCA is to define the Goal and Scope of the study. The goal of the study should clearly specify the following: the intended application; the reasons for carrying out the study; the intended audience; and whether the results are intended to be disclosed to the public. The scope of the study should include a description of the most important aspects of the study, including: the functional unit; system boundaries; cut-off criteria; allocation; impact assessment method; assumptions; and limitations.

The goal of Milestone 3 is to develop unit process building blocks and foundational carbon intensity values for Canadian low carbon fuel pathways. In contrast to Milestone 2, where the goal was to develop baseline carbon intensity values specifically for 2016 that will be set into Canadian regulations, the goal for Milestone 3 is to develop the unit process building blocks that low carbon fuel producers can use in the Fuel LCA Modelling Tool to calculate the carbon intensity of their unique low carbon fuel production processes. In addition, the goal is to calculate foundational carbon intensities for low carbon fuel pathways that are currently being produced in Canada, or that are expected to be produced in the next 5 years.

The results of the study and the methodology used to calculate the carbon intensities will be publicly available and will be used by fuel producers and ECCC policy analysts to compare the carbon intensity of current and future Canadian fuel pathways. These foundational carbon intensities and pathways will also be included in the Fuel LCA Modeling Tool, to be built in Milestone 4, for use in building low carbon pathways and comparing the carbon intensity of low carbon pathways to conventional fossil fuels. Modeling used for the pathways will be open and transparent to the user within the tool and downloadable in unit process form for review and use in other applications. The Fuel LCA Modeling Tool will also be publicly available so that policy analysts, fuel producers, and other researchers can use the tool to inform efforts to reduce the carbon intensity of Canadian fuels. As such, the study will be completed following the ISO 14040 and 14044 requirements for a full comparative LCA intended to support comparative assertions.

2.1 Function

The function of the liquid, solid, and gaseous fuel pathways analyzed in this study is to provide useable energy for transportation, industrial activities, and buildings in Canada. The fuel feedstocks considered in this analysis may serve other functions such as non-combustion uses (e.g., feedstocks, solvents or diluents) and use in industrial processes (e.g. steel production); however, these functions are not regulated under the CFS and are therefore excluded from the analysis (ECCC, 2018). Some fuels are also produced and used onsite by the fuel producer to produce a finished fuel or in facility operations. The CFS will regulate some of these “self-produced and used fuels” and they are included within the scope of this analysis (ECCC, 2018).

2.2 Functional Unit

A functional unit is defined as the quantified performance of a product system for use as a reference unit (ISO 2006a). This facilitates determination of reference flows for the system(s) being studied.

In this case, the function under study is the provision of fuel to power transportation, heating, and/or power generation. The functional unit is 1 MJ of fuel measured using the High Heating Value (HHV) at the regional distribution center.

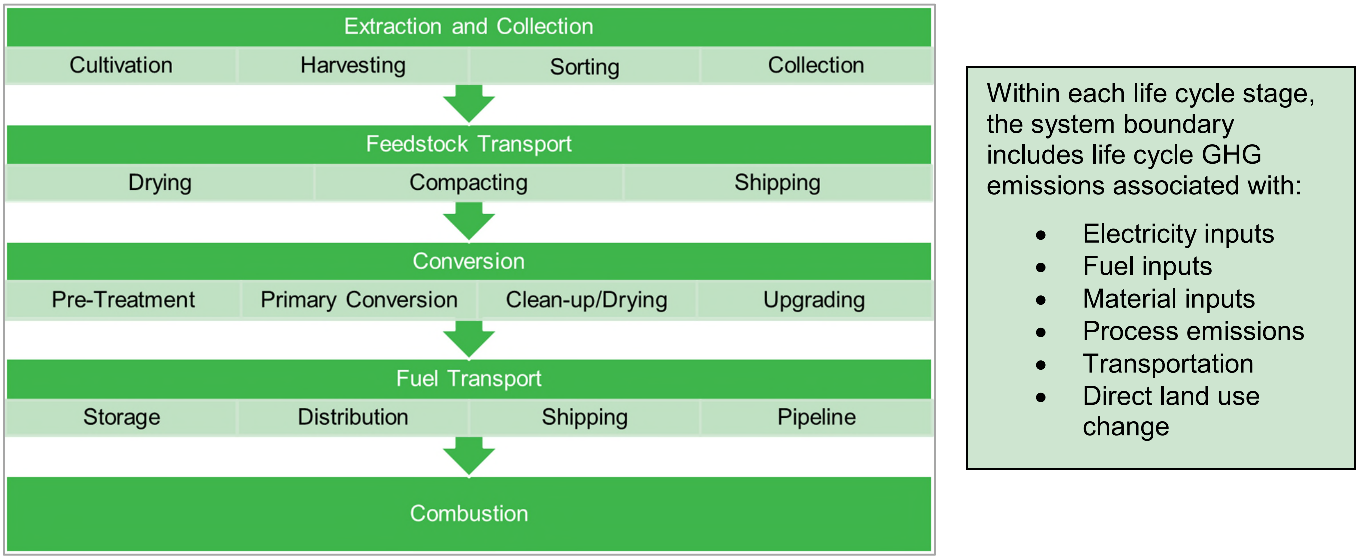
The carbon intensity values are expressed in grams of carbon dioxide equivalents (g CO_2 eq.) per unit of energy produced from combustion of the fuel in megajoules (MJ). Energy produced from fuel combustion is based on HHV and can be considered using different combustion efficiencies specific to the combustion type (e.g. heating, transportation, electricity). A single default combustion emission factor per fuel has been applied to generate the carbon intensity in most instances.

2.3 System Boundaries

System boundaries are established in LCA to include the significant life cycle stages and unit processes, as well as the associated environmental flows in the analysis. This lays the groundwork for a meaningful assessment where all important life cycle stages and the flows associated with each alternative are considered. The general system boundaries for the Fuel LCA Modelling Tool are consistent between fossil fuels and low carbon fuels, and include (Figure 1):

- **Extraction and Collection**: extraction of raw feedstock materials (e.g. cultivation of corn) or collection of co-products used as feedstock (e.g. forest harvest residues);
- **Feedstock Transport (transmission)**: transportation of raw or upgraded feedstock to the fuel producer, including any upgrading or processing required prior to transport;
- **Conversion**: processes for converting the feedstock into fuels, including any post-processing and upgrading to final fuel product;
- **Fuel Distribution**: storage and handling of fuel, transport of finished fuel product to storage and to final user; and
- **Combustion**: combustion of the final fuel product by the end user, taking into consideration the efficiency of combustion.

Within each of these life cycle stages, the system boundary also includes the life cycle GHG emissions associated with the use of electricity inputs (both grid and onsite generation), fuel inputs, material inputs (e.g. chemicals), process emissions (e.g. venting and flaring), transportation processes, and direct land use change. The inclusion of emissions from these background processes are determined by cut-off criteria (see Sections 2.5 and 2.6).



Within each life cycle stage, the system boundary includes life cycle GHG emissions associated with:

- Electricity inputs
- Fuel inputs
- Material inputs
- Process emissions
- Transportation
- Direct land use change

Figure 1. General system boundary for fossil fuels and low carbon fuels in the Fuel LCA Modelling Tool.

2.4 Fuel Production System Descriptions

Detailed descriptions of the system boundaries and fuel production systems are provided for each of the fuel pathways in Sections 4 through 11 in Part II of this report.

2.5 Cut-Off Criteria

Cut-off criteria are used in LCA practice for the selection of processes or flows to be included in the system boundary. The processes or flows below these cut-offs or thresholds may be excluded from the study. Several criteria are used in LCA practice to decide which inputs are to be considered, including mass, energy, and environmental significance. As noted in ISO 14044, making the initial identification of inputs based on mass contribution alone may result in important inputs being omitted from the study. As such, energy and environmental significance should also be used as cut-off criteria, particularly in studies intended to support comparative assertions made to the public. Options for cut-off criteria specified in ISO 14044 include:

- Mass: inclusion of all inputs that cumulatively contribute more than a defined percentage of the product system’s material inputs.
- Energy: inclusion of all inputs that cumulatively contribute more than a defined percentage of the product system’s energy inputs.
- Environmental significance: inclusion of inputs that are specially selected because of environmental relevance although they may fall below other cut-off criteria (e.g. mass).

Similar cut-off criteria may also be used to identify which outputs should be traced to the environment (e.g. emissions, wastes).

For this study, every effort was made to include all the relevant flows associated with the fuel pathways studied. During the interpretation phase, a 1% of environmental significance criterion, as calculated by the impact assessment method, was used to test the sensitivity of the results to assumptions and data substitutions made. Results of an economic input-output analysis for relevant sectors was conducted to inform the cut-off decisions, and a summary of these results is provided in Appendix D2. We also considered a 1% mass and energy-based cut-off to account for catalysts and other materials of small quantity. These cut-offs are diffused throughout the system, thus cumulative threshold for these cut-off criteria cannot be calculated using open source and transparent data as required for this study. In most, if not all cases, the cut off of these materials has been justified in the literature.

2.6 Excluded Processes

Typically, in an LCA, some aspects within the system boundaries are excluded due to statistical insignificance or irrelevancy to the goal. For example, the impacts of manufacturing and maintaining infrastructure associated with transportation systems and combustion technologies are highly variable and their contributions to life cycle impacts are negligible, so they are commonly excluded from LCAs of energy systems. The specific processes excluded from calculations of the CI for Canadian low carbon fuels include:

- Construction and decommissioning of agricultural equipment and facilities;
- Construction and decommissioning of forestry equipment and wood processing facilities;
- Construction and decommissioning of fuel conversion facilities and associated equipment;
- The manufacturing of fuel transportation infrastructure (i.e., pipelines, trucks, ships, roads);
- The manufacturing of fuel combustion infrastructure (i.e., vehicles, boilers);
- Solid waste management processes and wastewater treatment processes;
- GHG emissions associated with exported fuels;
- Research and development activities; and
- Indirect activities associated with fuel production, such as marketing, accounting, commuting, and legal activities.

Data for the processes excluded are in most cases highly proprietary and unavailable. The activities in general are also highly variable from project to project. Environmental Input Output data from the US indicates that the impacts from these activities are relatively small (<2%), so until we can measure them more accurately on a fuel by fuel basis, keeping them outside the boundary provides a more solid basis for comparison. This rationale applies to each of the excluded processes. See Appendix D2 for a summary of the I/O results that were used to inform the cut-off decisions.

It is also noted that since the Fuel LCA Modelling Tool does not rely on licensed LCA databases (e.g. ecoinvent), there are potentially other smaller life cycle activities that are excluded. The data sets in LCA databases typically include activities such as infrastructure manufacturing, waste and wastewater treatment, energy used to power combustion devices, etc. From a cumulative standpoint, these life cycle activities that make smaller contributions in isolation may not be negligible in total.

2.7 Assumptions

Based on data availability, several assumptions have been made and were tested to determine if they exceed the 1% environmental significance cut-off employed (except where noted that specific processes will be excluded). The assumptions for each fuel are documented in the report.

Some of the assumptions for the low carbon fuel pathways result in activities excluded from the system boundary based on both the cut-off criteria and the availability of data. Further detail on modeling assumptions for each fuel pathway is provided in the pathway-specific sections in Sections 4 through 11 of Part II.

2.8 Co-Product Allocation

While conducting an LCA, allocation situations occur where the studied system is a multifunctional process and not all outputs (or functions) are used for the considered functional unit. According to ISO 14044, allocation of the process inputs should be avoided by further sub-dividing the system to isolate co-products, or by using the system boundary expansion approach. If allocation cannot be avoided, an allocation method based on physical causality (mass or energy content, for example) or other relationships (economic value, etc.) should be used (ISO 2006b).

As part of developing the CFS, ECCC will define an approach for modeling multi-function systems. The current ECCC directive for co-product allocation is that when allocation is unavoidable, allocation should be based on underlying physical relationships. As stated in ISO 14044, allocation “should reflect the way in which inputs and outputs are changed by quantitative changes in the products or functions delivered by the system”. In fuel production systems, energy content, also known and referred to as the heating value, is generally recognized as the most appropriate metric. This allocation method offers the objectivity required for regulatory purposes and eliminates the subjectivity from the substitution and economic allocation methods. As such, ECCC recommends a hybrid approach, where the main method of allocation is by the physical relationship with energy content (mass content can be used as a proxy if energy data are not available). However, where applicable, emissions should not be applied to unused co-products (i.e. electricity produced by cogeneration would be attributed all the emissions if there is no heat user).

The choice of allocation method, while useful for standardization, transparency and clarity in decision making, is in fact a model choice and there are no “correct” or “right” ways to allocate. Allocation by energy will be used as the default approach, and the administrator version of the tool will allow for different allocations in the low carbon fuel pathways to be tested. Where allocation may be insufficient, and displacement more relevant, the displacement method can be used.

The need to allocate environmental burdens between products and co-products arises at several points in the life cycles of several low carbon fuel pathways, including:

- Anaerobic digestion, which produces both biogas and digestate;
- Agricultural and forest residues derived from primary cultivation and harvesting that are used to produce biofuels;
- Vegetable oil and meal produced from agricultural crops such as canola and soy;
- Animal feed or combined heat and power production from distillers' grains co-product of corn grain ethanol;
- Electricity generation from combustion of lignin in cellulosic ethanol production;
- Commodity chemical and other product production from lignin and hemicelluloses from cellulosic ethanol production; and
- Several low carbon fuel conversion processes which produce multiple outputs (e.g. biodiesel and glycerine).

For several of the energy pathways modelled in this study, wastes from other industrial activities are also used as feedstocks. The identification of an energy feedstock as a co-product or a waste has significant implications for the allocation of environmental burdens. In section 4.3.4.2 of the ISO 14044 guidelines, it is stated that environmental burdens should only be allocated to co-products and not to waste products (ISO 2006b). A waste is defined as a substance or object intended for disposal, while a co-product is defined as any of two or more products coming from the same unit process or product system (ISO 2006b).

In this study, system boundary expansion was used only in cases where an alternative co-product is a direct substitution for a fossil-based fuel or electricity. For all other co-products, allocation was made considering HHV, with the exception of forestry products. Because the majority of forestry products are used for and their value derived from non-fuel purposes, they are allocated based on mass, as per common convention.

Each baseline and foundational unit process in the Fuel LCA Modelling Tool will include data on HHV, LHV, mass, carbon content and hydrogen content. Provided this information is available, the user of the tool will be able to select the method of co-product allocation based on these factors. This will allow the user to change the allocation method throughout the pathway to see the results.

Waste products are handled differently than coproducts and separate empty unit processes will need to be created for user’s waste processes that are not in the database. The use of wastes as fuel feedstocks is an example of material recycling, and in this study we are using the cut-off approach to model recycling. The cut-off approach is part of an attributional LCA approach, and using this approach, if a waste material (first life) is used for another purpose (second life) instead of disposal, the producer of the waste material is not attributed any burdens for disposal, and the user of the waste material is not attributed any environmental burdens for the upstream production and handling of the material. The system boundary ends there, and any further environmental burden or benefit created by the second life is reliant upon market changes, and can only be modeled using market-based recycling, which is a consequential LCA modelling approach. As an example, if a low carbon fuel producer obtains organics from the MSW stream to produce ethanol, the first life (i.e. the producer of the organic waste) takes no burdens for disposal, while the second life (i.e. the low carbon fuel producer) takes no burdens for the production, collection, and storage of the organics. Using a consequential LCA approach, we might also model the changes in GHG emissions that would occur due to the removal of these organics from the waste stream; however, the carbon intensity calculations for fossil fuels and low carbon fuels are based on an attributional approach, and if consequential modelling is applied to waste feedstocks, then consequential modelling must be applied throughout the project. Background material on modelling recycling in LCA is provided in Appendix D. In the case that a waste product becomes a coproduct, it will have to be added to the unit process complete with its mass, HHV, LHV, density, carbon content, and hydrogen content.

For the purposes of the Milestone 3 report and results, a limited set of co-product allocation models have been developed based primarily on energy content, with some displacement and mass-based allocation in specific instances. During completion of the Fuel LCA Modelling Tool in Milestone 4, further data will be collected to add to the tool to enable multiple allocation and displacement options, including:

- Economic data for main products and co-products;
- Mass data for main products and co-products (where not presently defined);
- Definition of reference cases (business as usual) for displacement modelling; and
- Carbon intensity of selected materials and fuels that are displaced by co-products in the bioenergy pathways.

These data will be limited to the specific co-product allocation and displacement instances that are defined for the low carbon fuel pathways in the Milestone 3 report.

2.9 Impact Assessment Method

Impact assessment methods are used in LCA to convert life cycle inventory (LCI) data (environmental emissions and raw material extractions) into a set of environmental impacts.

The objective of this study is to calculate carbon intensity values for fossil fuel and low carbon fuel pathways, expressed in grams of CO_2 equivalents per MJ of energy. Carbon intensities include contributions to global warming from CO_2, CH_4, and N_2O, and others as appropriate, based on the IPCC factors for a 100-year time horizon. The 100-year time horizon is used as it is the characterization factor most-widely applied in fuels LCA thus facilitating ease of comparison to other study results. In this study the fossil methane factor of 30 was used for methane emissions. Table 1 provides a summary of the most recently updated characterization factors to calculate CO_2 eq from the IPCC. A complete list of greenhouse gases, impact factors, and the associated uncertainty can be found as an appendix to the Milestone 1 report (EarthShift Global, WSP, Introspective Systems 2019).

Table 1. Characterization factors for calculating carbon intensities using IPCC AR5 GWP 100.

Greenhouse Gas	IPCC AR5 GWP 100, excluding biogenic carbon
CO_2	1
CH_4 (fossil)	30
CH_4 (biogenic)	30
N_2O	265
Sulfur hexafluoride	23,500

2.10 Limitations of the Study

The work done under this project only pertains to fuels developed and used in Canada. Any conclusions or assumptions should not be applied to fuels developed or used elsewhere, where if production processes differ, the results will not be valid. Many of the low carbon fuels modelled in this report are not currently being produced at commercial scale in Canada, and so data and information on Canadian production systems is limited or not available. As such, the modelling for some pathways is based heavily on data from the literature and assumptions to extrapolate literature values to Canadian applications. This may result in significant over- or under-estimation of CI values in comparison with actual producer results.

2.11 Limitations of LCA Methodology

The ability of LCA to consider the entire life cycle of a product makes it an attractive tool for the assessment of potential environmental impacts. Nevertheless, similar to other environmental management analysis tools, LCA has several limitations. These can be related to data quality and unavailability of potentially relevant data.

The CFS is narrowly focused on carbon intensity or global warming potential. This means that fuels which offer the required reduction in carbon intensity may, in fact have worse environmental impacts than the baseline in other areas, such as water scarcity, eutrophication (excess nutrients), particulate emissions or toxicity. To understand the broader implications of a fuel pathway, a full LCA compliant with ISO 14044 is recommended.

Additionally, some environmental impacts are not included even in a full LCA, such as species migration and noise.

It should be kept in mind that even if a study has been critically reviewed, the impact assessment results are relative expressions and do not predict impacts on category endpoints (e.g. human health, wildlife species), exceedance of thresholds, or risks. If potential risks are associated with a pathway, an environmental and human health risk assessment and/or hazard assessment is recommended.

3. Modelling Approach for Low Carbon Fuels

3.1 Selection of pathways

The number of low carbon fuel pathways in research and development is large and growing. The scope and timing of this milestone did not allow for inclusion of all pathways, so a concerted effort was made to choose the most useful pathways with these attributes:

- Are in commercial production in Canada or elsewhere in the world, or whose viability is considered promising;
- Have feedstocks readily available in Canada; and
- Have publicly available research results to enable modeling.

Further streamlining chose pathways most likely to be brought to commercial scale. This selection was made in consultation between ECCC, the CFS team, and the authors in Milestone 1 of this project (EarthShift Global, WSP, Introspective Systems, 2019a).

3.2 LCI Data Collection

The scope and timing of this project did not allow for the project team to collect primary data from Canadian low carbon fuel producers. As such, data collection to develop the LCI was based on review and compilation of data from a range of secondary sources on Canadian fuel pathways. Data sources used included government publications and statistics, industry publications and statistics, other fuel LCA modelling tools, as well as literature data for low carbon fuel systems with little or no current production in Canada. The exception to this approach was for ethanol and biodiesel production, where several years of primary operating data was available for a large segment of Canadian ethanol and biodiesel producers. A brief overview of the LCI data considerations for low carbon fuels is provided below.

3.2.1 LCI Sources for Low Carbon Fuel Pathways

In general, the low carbon fuel pathways are not as well-established as the fossil fuel pathways, with many in earlier stages of development and having not reached commercial-scale production. The availability of Canadian-specific data was limited for several of the low carbon pathways as a result, requiring decisions to be made on what to include and ensuring proper documentation of data quality.

Aside from hydrogen, the low carbon fuel pathways are generally based on three feedstock types, including agricultural feedstocks, wood fibre feedstocks, and waste feedstocks.

3.2.1.1 Low Carbon Fuel Feedstock Extraction and Collection

Agricultural Feedstocks

Primary and secondary products (products, co-products and wastes) from several key Canadian crops supply feedstock for a large portion of the low carbon fuel pathways. These key feedstocks include primary products, co-products and residues from: corn; wheat; soy; canola; barley; and camelina. There can be considerable variation in the carbon intensity of these feedstocks across different regions of Canada, and efforts were made to capture regional variability for these feedstocks. The agricultural LCI and associated carbon intensity values are described in more detail in Section 4.

Dr. Nathan Pelletier's ongoing research to develop a LCI database for key Canadian crops (Canadian Agri-food Life Cycle Data Centre (CALDC)) provided a significant amount of the required data to develop regionally-defined carbon intensity values for all of these crops with the exception of camelina and peas. Key features of the CALDC will include:

- A publicly available tool, with a user-friendly web interface;
- Maximally interoperable with other LCI databases and LCA software packages, including any eventual Canadian or North American LCI data repositories;
- Data set import and export functionalities;
- Transparent data quality/uncertainty reporting based on existing best practices;
- Periodically updated;
- Hosting LCI datasets for the majority of common agri-food supply chain activities and commodities in Canada; and
- Supported by and utilized by a partnership of industry, government, and academic stakeholders.

While the database is not yet online, the data are readily available upon request.

Additional data for agricultural feedstocks and validation of the CALDC LCI data was obtained through consultation and reporting from Agriculture and Agri-Food Canada. More specific data sources for agricultural feedstocks are summarized in Section 4.

Wood Fibre Feedstocks

Primary and secondary products from wood harvesting and wood product manufacturing also supply feedstock for a large number of fuel pathways, including pyrolysis oils, several solid fuel pathways, as well as hydrogen, biogas, and renewable natural gas (RNG). These feedstocks are derived from primary forest harvest, primary harvest residues, sawmill and wood product manufacturing residues, and construction and demolition waste. There has been a significant amount of LCI data generated for the life cycle of a number of these wood feedstocks in different Canadian provinces. There are some aspects of wood fuel pathways that vary from region to region, including harvesting practices (i.e. fuel use), feedstock availability, and background energy systems for wood feedstock processing (e.g. electricity use during pelletization). These variations are accounted for where possible. More specific data sources for wood fibre feedstocks are summarized in Section 10.3.1.

Wastes

Wastes from various agricultural, commercial, and industrial activities are used as feedstock for many of the low carbon fuel pathways, including ethanol, biodiesel, biogas/RNG, and solid fuel pathways. These feedstocks include municipal solid waste (MSW), wastewater treatment (WWT) sludge, oils and grease, animal fats, manure, and industrial/Construction and Demolition (C&D) waste. In line with ISO 14044 guidance, the upstream GHG emissions are not allocated to feedstocks that are considered waste products. Based on this choice, the life cycle carbon intensity for these feedstocks begins at waste collection and processing. More specific data sources and assumptions for waste feedstocks are provided in each of the fuel pathway sections in Part II.

3.2.1.2 Low Carbon Fuel Conversion

There are a wide range of conversion technologies used to convert feedstocks to low carbon fuels depending on the desired end-use. Life cycle inventory data needs for conversion technologies include:

- Mass balance data for feedstock conversion efficiency;
- Energy inputs (electricity (grid and on-site generation, fuels); and
- Material inputs (chemicals, enzymes, etc.).

For biodiesel and ethanol production, primary data from Canadian producers was used to model the fuel conversion process. For other fuel conversion processes in other low carbon fuel pathways, literature was used and adapted to Canadian conditions where possible (e.g. background energy source). More specific data sources for low carbon fuel conversion technologies are outlined in each of the fuel pathway sections in Part II.

3.2.1.3 Low Carbon Fuel Combustion

The system boundary for calculation of carbon intensity values for low carbon fuels in the Fuel LCA Modelling tool includes GHG emissions from combustion of low carbon fuels for industrial energy, space heating, and transportation. Data on the GHG emissions from low carbon fuel combustion were obtained from Canadian government emissions factors used in other government programs for GHG emissions accounting. In instances where specific emissions factors for low carbon fuels were either not available from the Canadian government, or for which it was determined that higher quality data could be obtained, these emissions factors were supplemented with values from literature and other government carbon regulatory programs and tools (e.g. GREET, CARB, or GHGenius 4.03). An explanation of the treatment of biogenic carbon emissions from fuel combustion is provided in Section 3.5.3.

3.2.2 LCI Data for Commonly Used Unit Processes

Throughout the low carbon fuel pathways there are a number of commonly used unit processes that are used in multiple unit processes. These include:

- **Materials and Chemicals**
    - Fertilizers;
    - Herbicides;
    - Pesticides;
    - Enzymes;
    - Acids;
    - Catalysts;
    - Other chemicals as identified during Milestones 2 and 3.
- **Electricity**
    - Provincial electricity grids;
    - Individual electricity generation types.
- **Fuels**
    - Natural gas combusted in equipment;
    - Diesel combusted in equipment;
    - Heavy and light fuel oil in equipment;
    - Gasoline combusted in equipment;
    - Propane combusted in equipment.
- **Transportation**
    - Tractor trailer, diesel;
    - Tractor trailer, gasoline;
    - Truck, diesel;
    - Truck, gasoline;
    - Train, diesel;
    - Container ship;
    - Pipelines.
- **Process Emissions**
    - On-field nitrogen emissions from fertilizers;
    - On-field emissions from tilling.

Inventory data for these commonly used unit processes are being stored in the CFS Modelling Tool data library so that all fossil fuel and low carbon fuel pathways can use them. For example, fossil fuel production and transport processes that were modelled in Milestone 2 were also used in Milestone 3 to provide inventory data for low carbon fuel life cycle activities. Data sources for other commonly used processes are summarized in each of the individual fuel pathway sections in Part II.

More details on the LCI data and the sources used to compile the LCI are provided in the individual fuel pathway sections in Part II of the report. The LCI data and calculations have been carefully documented to ensure transparency and the data templates developed include detailed meta data and uncertainty data. The data sheets and supporting calculations sheets (where required) have been provided as a supporting information package with this report. The selection of data for use was guided by data quality preferences developed for the project and by ISO guidance on data consistency and completeness.

3.3 Data Quality Preferences

The LCI data used in the low carbon fuel modeling is a mixture of data that is either specific to Canadian systems, data from other jurisdictions that is considered adequately representative and modified to include Canadian energy and emissions, or data from other jurisdictions that is considered adequately representative without revision. The LCI data also include a mixture of verified (audited) data based on measurements by producers that report data, as well as non-verified data obtained from the literature that was modified with expert judgment and assumptions.

The ISO guidelines indicate that data quality requirements should be specified to enable the goal and scope of the LCA to be met (ISO, 2006b). In this section, we outline a set of data quality preferences established for the Fuel LCA Modelling Tool and that were applied in modelling low carbon fuel pathways.

3.3.1 Foreground Unit Processes

The foreground unit processes for this project include the primary activities involved in extracting and producing the fuel feedstocks, transporting and processing feedstocks, converting feedstocks to useful energy, and emissions from the energy application. Due to the importance of these activities in quantifying life cycle impacts and determining the representativeness of the CFS tool for Canadian fuel pathways, we have made every attempt to use the highest quality Canadian data to characterize the inputs and outputs of all foreground unit processes. More specific data quality requirements for foreground unit processes are shown below in order of priority:

1. Regionally specific Canadian data from verified sources (e.g. producers, government statistics, data collected for Canadian life cycle inventory databases) for the specific industry/technology under study.
2. Regionally-specific Canadian data from published literature and academic studies.
3. Canadian-average data from verified sources for the specific industry/technology under study (e.g. producers, government statistics).
4. Regionally-specific or national average Canadian data from non-verified sources for the specific industry/technology under study.
5. North American data using the same hierarchy above.
6. United States data from verified sources from the specific industry/technology under study, updated to reflect Canadian background energy systems or conditions where possible.
7. United States data from verified sources from the specific industry/technology under study.
8. Verified data from outside Canada and the United States for the specific industry/technology under study.

In general, the level of data quality for foreground processes decreases as one moves down this hierarchy. This is reflected in the data quality assessment and accounted for in the uncertainty analysis.

3.3.2 Background Unit Processes

The background unit processes for this project include upstream activities that support foreground process activities, for example the production of electricity to supply an industrial activity. Although in the background, these activities can still make significant contributions to the life cycle GHG emissions of Canadian fuel pathways; however, some background activities have low to negligible influence on the carbon intensity of Canadian fuel pathways (e.g. fuels transported by pipeline for short distances, small percentages of crude transported by tanker ship) and the data quality requirements are therefore less stringent for these unit processes. The data quality requirements for background unit processes are the same as those identified above for foreground unit processes, with the exception that non-verified data from outside Canada and the United States may be considered for instances where the process being modeled is not a significant contributor of life cycle GHG emissions. This does not mean that these data are not included. It means that the data are included, but from sources that are not specific to Canada or the timeframe of modeling in lieu of specific data availability.

3.4 Quantifying Data Quality and Uncertainty

In practice, all data used in an LCA study is a mixture of measured, estimated and calculated data. To evaluate the quality of the data used for modeling the fuel pathways, Data Quality Indicators (DQI) are used to assess each flow and linked pathway using a data quality matrix approach. These scores are also used to assess uncertainties on the data and subsequently assess the uncertainty of the model and the results.

Accounting for uncertainty is an important aspect in development of the Fuel LCA Modeling Tool because this information provides appropriate context for decision-making when evaluating the potential carbon intensity of alternative fuel pathways, and because it influences the modeling process itself. The Conceptual Model was developed to include uncertainty analysis capabilities for input values, modeling choices, and uncertainty propagation and interpretation. For advanced users aiming to inform policy decisions, uncertainty information can be particularly helpful in identifying a preferred fuel pathway among several options in a way that is transparent and can be justified. This can include comparative decisions among different available pathways, or to compare potential variations in carbon intensity for a single pathway in order to define regulatory targets.

The model distinguishes between two types of uncertainty: parameter and model. Parameter uncertainty is the uncertainty concerning input values. In the case of LCA models, this refers to the amount of a flow. For instance, uncertainty on the number of kWh of electricity required in a certain fuel conversion process, or uncertainty in the amount of carbon emitted during combustion of a fuel. The uncertainty in inventory data can derive from a lack of knowledge of a certain system, or from variability. Uncertainty in combustion emissions, for instance, may be from differences in engine technology, processing facilities, and/or atmospheric temperatures on the day of the emissions measurement. The more variability the inventory can reflect, the less uncertainty there is, although this also makes the results less generalizable. This means that when we develop very process and technology-specific data sets, it reduces uncertainty in the data relative to that specific process or technology, but in turn it means that this data set is not as useful to apply to a broader range of processes or technologies in that sector. For example, consider the inventory for a certain crop for which production and yield can vary depending on the soil type and farming practices. An average inventory on a per kg basis of harvested crop would combine the range of inputs representing the different soil types and farming practices. The uncertainty in such inventory is be partially due to this variability. Another approach is to create several versions of the inventory to account for both sources of variability: soil type and farming practices. In the case of four different soil types and five different farming practices, one could have twenty different processes.

Further parameter uncertainty has been applied to the fitness for purpose of the underlying data. This takes into account the use of data which are not ideal because they come from a different geographic location, time period, or technology.

Often the life cycle inventory is derived from multiple studies where the most representative and generalizable inventory is obtained from a combination of information. Therefore, an LCA model, for pragmatic reasons, must balance variability so that the inventory is representative enough and applicable. Uncertainty due to lack of knowledge is included as parameter uncertainty.

The uncertainty of the fossil fuel pathway parameters has been modeled in one of two ways as shown in the decision trees in Appendix B of the Milestone 1 report (EarthShift Global, WSP, Introspective Systems 2019). Where a range of values is available based on different refineries, reports, or calculations, the full range is used using a uniform distribution. Where a range is not known, the pedigree matrix is applied as a Bayesian method of assessing probability.

3.5 Modeling Approach and Carbon Intensity Calculations for Low Carbon Fuels

In contrast to the LCA modelling work completed in Milestone 2, many of the low carbon fuel pathways are not well-established commercial fuels in Canada, and in some cases very limited information is available on Canadian production and use, if at all. In many instances, only literature data is available, or only single data sets from demonstration-scale or theoretical production simulations. The notable exceptions to this are ethanol and biodiesel, for which very reliable Canadian LCI data were available on feedstock production and fuel conversion. As a result of this, the CI calculations for low carbon fuels are generally not production-weighted averages for a single year of production as the fossil fuel CI values were in M2; rather, in most cases the CI values for low carbon fuels are representative of single facilities or average data for a typical feedstock or conversion technology configuration. The expectation is that users of the Fuel LCA Modelling Tool will provide more representative and robust Canadian data over time.

Based on this, while the primary objective for Milestone 2 was to develop baseline carbon intensity values for fossil fuel production and use in 2016 to be used in Clean Fuel Standard (CFS) regulations, the primary objective in Milestone 3 is to develop default carbon intensities for low carbon fuel pathways along with a collection of basic unit processes that could support future use of the LCA Modelling Tool. This will allow low carbon fuel producers to develop carbon intensities for their unique low carbon fuel pathways by using and modifying the basic unit processes provided using more recent data or more Canadian-specific and process-specific data.

The following sections provide a brief overview of the modelling approach for low carbon solid fuels, as well as discussion of some key methodological issues to be addressed in the modelling.

3.5.1 Development of Unit Process Building Blocks

The overall modelling approach for Milestone 3 is to develop unit processes to serve as building blocks for current and future modelling work in the Fuel LCA Modelling Tool. This is in contrast to the development of production-weighted 2016 average CI values for fossil fuels in Milestone 2. The low carbon fuels industry is still in development in Canada with many different emerging technologies; however, many of these emerging technologies are reliant on a core set of feedstock sources and conversion processes that are relevant for many different pathways. For example, in the case of fuel pathways that rely on wood biomass or agricultural feedstocks this approach is particularly relevant since there are a variety of fuel feedstocks that may be used in any fuel conversion process, and these are all based on a basic set of feedstocks that are produced within the Canadian forestry supply chain (or in the case of corn stover pellets, from the Canadian agricultural industry) and within the Canadian agricultural sector. So even in an instance where a low carbon fuel producer has developed a novel fuel conversion technology for biomass energy, they will still need modelling data for cultivation, harvesting, pre-processing, and transport of the required feedstocks. The building blocks approach also allows users of the Fuel LCA Modelling Tool to easily quantify the GHG emissions associated with alternative feedstocks that are available to them, for example to inform the decision whether to use sawmill residuals or unmerchantable roundwood as a feedstock by providing the ability to quickly model the CI for different feedstocks that can serve the same purpose.

The use of this building blocks approach is also intended to account for the lack of available data to model Canadian low carbon fuel systems. By taking this approach, even in cases where only literature data is available, or where no data is available, unit processes can still be developed and included as placeholders in the Fuel LCA Modelling Tool and can then be updated by tool users when data is available in the future.

The modelling work in Milestone 3 also relies heavily on fossil fuel unit processes that were developed in Milestone 2, including fuel inputs to machinery and equipment (e.g. diesel, natural gas, etc.) and transportation processes (e.g. trucks, rail, pipelines). These unit processes are stored in the ECCC Fuels database and have been incorporated into the low carbon fuel pathway models where needed.

3.5.2 Regional Variation

A number of aspects of low carbon fuel production systems in Canada are influenced by changing conditions across different regions of Canada. Although there is presently a lack of well-established, regionally-based low carbon fuel producers in Canada, the incorporation of regional variability is important and may provide useful data for informing low carbon fuel producers about the most suitable locations and feedstock options from a carbon intensity standpoint.

There are a number of regional factors which could influence carbon intensity for low carbon fuels. These include:

- Differences in fuel consumption in forest harvesting, sawmilling and other processing activities;
- Inputs and crop management practices for Canadian crops across different provinces and regions;
- Background energy systems such as variations in electricity grids providing energy to fuel conversion processes; and
- The sourcing of regional/provincial feedstocks could also influence transport distances and modes for feedstock delivery and final fuel delivery.

These differences have been reflected in the modelling as much as possible within the confines of the available data. Particular emphasis was placed on accounting for differences in the carbon intensity of provincial electricity grids, as electricity inputs are significant contributors to the life cycle carbon intensity of many of the low carbon fuel pathways, in particular because many of the fuel conversion processes are energy intensive and rely on electricity. More specific details on the inclusion of regional variability are provided in each of the fuel pathway sections in Part II.

3.5.3 Biogenic Carbon and Land Use Change

In remaining consistent with the Government of Canada’s policy on biogenic carbon, as shown in Canada’s National Inventory Report (Government of Canada, 2018), emissions of biogenic carbon from combustion of low carbon fuels were not included in the carbon intensity calculations. Biogenic carbon emissions will be calculated and reported separately from the default carbon intensity values.

Carbon emissions associated with direct land use change were included in instances where feedstock production requires the conversion of land from existing use to bioenergy production; however, it has generally been assumed that provision of agricultural and wood biomass feedstocks is within the capacity of existing commercial production and harvesting regions and does not require conversion of land from other uses. As the Canadian low carbon fuel industry grows in scale, this assumption may need to be revisited and revised. Some specific instances of direct land use change has been modelled for Canadian crops, such as carbon emissions from tillage practices and changes in annual/perennial crops. During development of the Fuel LCA Modelling Tool in Milestone 4, generic factors for GHG emissions from other direct conversion of standard land use types (e.g. conversion of forest to agriculture) will be added where available so that DLUC can be quantified in the future. These emissions factors will be drawn from the literature and may require additional refining and updating in future iterations of the tool. Following a Canadian policy decision, indirect land use change (iLUC) is excluded from the carbon intensity calculations. More specific details on the inclusion of land use change is provided in each of the fuel pathway sections in Part II.

Part II: Low Carbon Fuel Pathway Models and Carbon Intensity Results

4. Agricultural Systems for Crop-Based Low Carbon Liquid Fuels

Life cycle inventories for commodity field crop production were compiled for six crops: corn, wheat, barley, canola, soybean, and camelina[1]. These are used to calculate Carbon Intensity values for both harvested crops and crop residues. This section describes methods used to compile and calculate provincial, production-weighted life cycle inventories and the associated Carbon Intensities for major cereal grain and oilseed crops in Canada for the crop-based low carbon fuel pathways and other uses.

The Carbon Footprint Methodology report from the Canadian Roundtable for Sustainable Crops (CRSC) carbon footprint studies, along with the crop-specific CRSC reports for corn, wheat, barley, canola and soybean, were the main sources of data for compiling these inventory tables. The camelina inventory was largely constructed using data provided by Smart Earth Seeds and Saskatchewan Agriculture, but on a similar methodological basis so as to ensure comparability across inventories. Crop residue data were updated for all crops based on recent literature. Seeding rates and pesticide application rates for canola were also updated. Inventories were first compiled at the reconciliation unit level in keeping with the CRSC reports, then scaled on a production-weighted average basis to the provincial level. Similarly, the provincial level values are used to calculate production-weighted average national values. The agricultural LCIs are used to calculate provincial and national average carbon intensities for use in the crop-based (Section 5) and residue based (Section 6) low carbon fuels.

4.1 Overview of Agricultural LCI Development

Life cycle inventories for field crop production were first compiled at the reconciliation unit level, based on the CRSC reports and other sources. These are provided in Dataset[2] A1. Production and area of farms were subsequently used to calculate production-weighted inventories for each crop and province. These data are provided in Dataset A2. The methods for inventory data collection are described in (S&T)2 Consultants Inc. (2017), and most data are derived from the related CRSC Carbon Footprint study reports for each crop (with the exception of camelina, which was not considered in the CRSC studies) ((S&T)2 Consultants Inc., 2017a, 2017b, 2017c, 2017d, 2017e, 2017f).

The CRSC studies represent the current best available source of Canadian field crop life cycle inventory data. Additional data and updated data were obtained for crop

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[1] A detailed LCI for Canadian peas is anticipated to be incorporated into the CALDC library during 2020. In the interim, the carbon intensity (Desjardins, et al., 2016) has been used.

[2] Dataset A1 and Dataset A2 are available as Excel files with the raw data (A1) along with the weighted and aggregated data (A2). Any specific issues for each data category or production process, as well as issues with individual data points, are noted as comments in the appropriate cell in those workbooks.

residues from (Thiagarajan, Fan, McConkey, Janzen, & Campbell, 2018). Updated data for pesticide application rates and seeding rates for canola were obtained from a report on GHG emissions for canola oilseed submitted by Canada to the EU as per Renewable Energy Directive requirements for accessing the EU biofuel feedstock market (European Commission, 2016). Finally, an LCI was developed for camelina using comparable methods.

4.1.1 Production-weighting

The first set of crop inventories (Dataset A1) are reported at the reconciliation unit (RU) level, as per the CRSC reports. The second set of inventories (Dataset A2) are production-weighted provincial average inventories. This dataset (Dataset A2) was created by scaling the Dataset A1 using production-weighted average data for each RU in a given province. In addition, the Dataset A2 includes calculations for nitrous oxide (N_2O) emissions related to nutrient management and crop residues.

It should be noted that despite the ambition of achieving RU-level resolution in the CRSC studies, many data were only available at coarser levels of spatial resolution (for example, provincial, regional, or national data). National data, such as direct energy use for corn and soybean and pesticide application for barley, were not scaled down to province level, as it would incorrectly represent the spatial resolution of data. However, when provincial data for one province were used as proxy data for other provinces, such as pesticide application for corn, wheat, and soybean, provincial averages (production-weighted) were calculated for Dataset A2, implying that there was downscaling for some provinces. These factors were incorporated into the crop-specific uncertainty factors for each crop.

4.2 Scope of the agricultural LCI

Activities spanning soil preparation until harvesting and storage were considered for corn, wheat, barley, canola, soybean, and camelina. Separate inventories were developed for durum wheat and all other varieties of wheat. For other crops, different varieties and cultivars were aggregated in one inventory. The inventories are expressed in terms of a functional unit of one tonne of grain or oilseed, with assumed moisture contents as per Table 2.

According to Smart Earth Seeds, the leading contractor for camelina breeding and production, 8% moisture is optimal for camelina grain storage (Smart Earth Seeds, 2019). The Saskatchewan Crop Planning Guides (Government of Saskatchewan, 2017, 2018, 2019) also recommend <8% moisture for safe storage of camelina, hence this value was adopted for the camelina inventory.

Table 2. Moisture content of studied field crops

Crop	Moisture content (%)	Dry matter (%)
corn	14.5	85.5
wheat	13.5	86.5
durum wheat	14.5	85.5
barley	13.5	86.5
canola	8.5	91.5
soybean	12.0	88.0
camelina	8.0	92.0

Reported data for each inventory includes the direct inputs into the crop production process, but excludes:

- the (upstream) production of those inputs, such as:
    - production of field inputs, such as seeds, fertilizers, and pesticides
    - production of energy, such as fuel production, and electricity generation
    - on-farm production of renewable energy, such as solar, wind, and biomass combustion
    - ancillary operations, such as work area lighting and heating
    - manufacture, maintenance and decommissioning of capital equipment
- the subsequent (downstream) use phase of the output grains and oilseeds, such as:
    - further processing into food products or animal feed
    - transport and distribution
- waste streams, such as:
    - disposal of process wastes
    - straw and stover,
    - field emissions from manure application, which was allocated to the corresponding livestock system
- upstream inputs for irrigation water.

A key contention in carbon footprint and LCA methodology is whether or not to include soil carbon changes as part of the modeling. These LCIs include the calculation of soil carbon changes resulting from three types of land management changes: perennial to annual, reduced summer fallow, and reduced tillage, as per the CRSC methodology (this is discussed further in the section Soil Organic Carbon Changes, below).

The geographical coverage of the LCIs includes all RUs with more than 10,000 ha of cropland (before distinguishing between types of crop grown). For camelina, although agronomic experiments have been carried out in all of Western Canada (Smart Earth Seeds, Johnson et al. 2010), they were primarily conducted in Saskatchewan. Until more information becomes available, it was assumed that all camelina production is occurring in Saskatchewan. Since most camelina production is occurring in Rural Municipalities within the brown and dark brown soil zones in Saskatchewan (Vakulabharanam, 2014), which mostly fall within the Semiarid Prairies (RU 30), it was assumed that all camelina production falls within RU 30. Li & Mupondwa (2014) also assumed that camelina was grown in the brown and dark brown soil zones, when they calculated N_2O emissions.

Although the inventories are intended to represent average production within a one year time frame, the temporal representativeness of specific data points often varies. Temporal coverage may vary between data categories (e.g. seeding rate), and even within data points in the same data category, as per best available data sources. Specific temporal coverages are described in the subsequent sections.

Eight production processes were included: tillage, seeding, irrigation, fertilizer application, pesticide application, harvesting, transportation of the product from the field to the on-farm storage bin, and storage (including aeration/drying). Fuel and energy consumption were considered for all processes. Crop residues left on the field after harvesting were also included. Figure 2 illustrates the process flow, including the inputs considered, and functional unit.

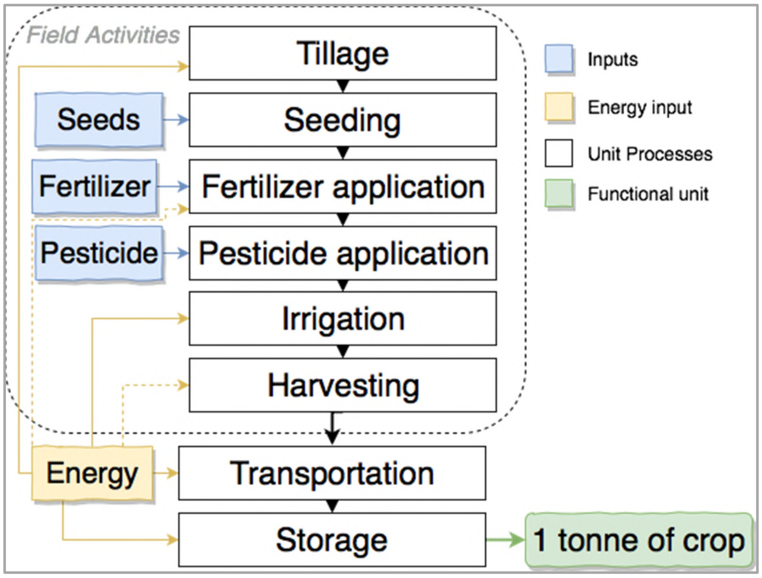

Figure 2. Process Flow Diagram, including inputs, processes and functional unit of studied crops

Technological coverage also varies, in particular with respect to tillage operations and types of fertilizers. Type of tillage was considered for the calculation of (a) tillage energy use in the form of diesel fuel consumption, (b) Emission Factor 1 for direct N_2O emissions, and (c) soil carbon changes. Three tillage types were modeled: (1) conventional tillage or intensive tillage (IT), (2) reduced tillage (RT), and (3) direct seeding or no-tillage (NT). Types of fertilizer used are distinguished by province, but generally not by crop, and time of application is not distinguished.

4.3 Data Sources

Data sources used in the CRSC Carbon Footprint Reports were:

- Yield and production data were obtained from Statistics Canada (from the now-retired CANSIM Table 001-0071), on a Small Area Data (SAD) basis for all provinces except the Atlantic Canada provinces, where data was obtained at the province level.
- Fertilizer application rates were obtained from

  - the Manitoba and Saskatchewan Crop Insurance programs, which provide detailed, long-term databases for fertilizer application rates that are geo-referenced for each crop that is insured (Saskatchewan Crop Insurance Corporation, 2019) (Saskatchewan Crop Insurance Corporation, 2015);
  - Fertilizer Use Surveys by Stratus Ag Research (Stratus Ag Research, 2015); and
  - Provincial field crop budgets
- Fertilizer type by province were obtained from
  - Statistics Canada (2016), based on shipments to provinces; and
  - Fertilizer Use Surveys by Stratus Ag Research (Stratus Ag Research, 2015)
- Pesticide use data were obtained from Farm and Food Care Ontario (2015) for 2013 and 2014, Group Ageco (2015), USDA NASS (2015), and USDA (n.d.)
- Data for direct energy use were obtained from Prairie Crop Energy Model (PCEM) (uncited), tillage data from the 2011 Agricultural Census (uncited), and USDA (2012).
- RU-specific N_2O emission factors for 2014 were obtained from the National Inventory Report by AAFC (AAFC, 2015)
- RU-specific soil carbon changes were provided by AAFC, and were calculated based on IPCC (2006) methods as adapted for Canada

More detailed information about data sources can be found in the individual subsections under Section Data categories, and as comments on individual cells in the LCI tables (Datasets A1 and A2).

Additional data sources are:

- Crop Residues from Thiagarajan et al. (2018), which referenced Fan et al. (2017), from which more details were obtained
- Seeding rates and pesticide application rates from the report on GHG emissions of cultivation of canola oilseed in Canada submitted to the European Commission (2016)
- Data sources used for camelina are varied and not comparable to the other five crops. Growing camelina is by contract only, and contractors may not share all information they have. Data sources are provided in the individual subsections under Section Data categories.

These data sources are provided in References list.

4.4 Data categories in the Agricultural LCI

4.4.1 Production data

Harvested area and production data were obtained from Statistics Canada (2012, 2013, 2014) on a Small Area Data (SAD) basis from the now retired CANSIM Table 001-0071 and used to calculate the yield, based on the average from three years from 2012 to 2014. SAD was converted to an RU basis by assuming an equal distribution of production through the small area region and using GIS software to aggregate and or divide the Small Area Data to the appropriate RU.

Yield was recalculated for these LCI tables in order to calculate the additional inventory items to the appropriate level of precision. Harvested area and production data were obtained directly from the CRSC reports and were not recalculated.

For Dataset A2, harvest area and production were aggregated to the provincial level, from which provincial average yield was calculated. These values were used for all subsequent production weighting and provincial averaging.

Camelina is not one of the fifteen Canadian Principal Field Crops for which production data are available from Statistics Canada. Further, unlike other more established field crops, camelina yields will fluctuate, as reflected by the Saskatchewan Crop Planning Guides from 2017 to 2019, and will increase as new cultivars are being developed and added to commercial production (e.g. MIDAS and SES0787LS (Smart Earth Seeds, 2019)). Area grown in Saskatchewan was assumed to be 1459 ha, based on the average camelina acreage for 2016 to 2018 from Saskatchewan Crop Insurance Corporation (SCIC) customers (Saskatchewan Crop Insurance Corporation, 2019), and assuming that 73% of camelina growers in Saskatchewan are SCIC customers.[3] Camelina yield was taken to be 1.129 tonnes/ha, based on the average yield of Saskatchewan Crop Insurance Corporation (SCIC) customers from 2016 to 2018, which roughly coincides with the yield of the calena cultivar (Smart Earth Seeds, n.d.).

4.4.2 Seeding Rates

Higher quality data were available for seeding rates of canola in RU 23 and 24 in Manitoba, RU 28, 29 and 30 in Saskatchewan, and RU 34, 35 and 37 in Alberta based on the European Commission (2016) canola report, which was derived from the 2011 survey of canola farmers by the Canola Council of Canada. A value of 5.6 kg/ha has been assumed for the RUs in NB and BC based on the recommended seeding rate from the Saskatchewan Crop Planning Guide 2015, according to the CRSC Canola report. 5.6 kg/ha also corroborates with the canola guidelines from Manitoba Agriculture (2018) and the 2019 Saskatchewan Crop Planning Guide (Saskatchewan Agriculture, 2019).

From the CRSC reports, actual data on seeding rates for field crops in Canada were only found for Quebec (CECPA, 2016) and were based on a relatively small sample of producers. Recommended seeding rates are included in the Manitoba MyFarm Crop Calculator (Manitoba Agriculture, 2016), Saskatchewan Crop Planning Guide (Saskatchewan Agriculture, 2016), and the Ontario Field Crop Budgets (Ontario Ministry of Agriculture, 2015). The Saskatchewan Crop Planning Guide reports seeding rate recommendations for each soil zone, as well as values for both feed and malting barley, whereby the average of the two was used. For the other provinces and other crops, inventory data relied on USDA (2009, 2010, n.d.) ARMS data, and averages or assumptions from the other provinces.

Camelina seeding rate was assumed to be 6.7 kg/ha according to the 2019 Saskatchewan Crop Planning Guide (Saskatchewan Agriculture, 2019). The guide also estimated that there are 650,000 seeds/kg, which gives a seeding rate of approximately

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[3] SCIC insures between 73% to 75% of seeded acres for annual grain crops in Saskatchewan.

4.4 million seeds/ha. This is roughly comparable to the seeding rate of 5.5 to 7 million seeds/ha in a field trial conducted in Saskatchewan (Johnson et al., 2010).

4.4.3 Fertilizer Application Rates

The following table (Table 3) summarizes the data sources from the CRSC reports that were used as the basis of fertilizer application rates for each crop and province.

Table 3. Data sources for fertilizer application rates of different crops

Crop	Provinces	Sources	Years
corn, wheat, barley, canola, soybean	Manitoba	Manitoba Management Plus Program	Average of 2012-2014 (citation year 2015)
wheat, durum wheat, barley, canola	Saskatchewan	Saskatchewan Crop Insurance Corporation	Average of 2012-2014 (citation year 2015, 2016)
corn	Ontario and Quebec	Stratus Fertilizer Use Survey	2015 and 2016
wheat	Ontario and Quebec	Stratus Fertilizer Use Survey	2016
	Alberta		2015
durum wheat	Alberta	Alberta crop budget	2015
barley, canola	Alberta	Stratus Fertilizer Use Survey	2016
barley	Ontario	Field crop budget	2016 (citation year 2015)
barley	Quebec	CECPA benchmarking report	2014 (citation year 2016)
soybean	Ontario and Quebec	Stratus Fertilizer Use Survey	2015
camelina	Saskatchewan	Crop Planning Guide	2019

No data or crop budget was available for the other provinces; therefore, assumptions or national average values were used.

Since data from the CRSC Canola Carbon Footprint report was the most recent source, it was used to calculate fertilizer application rate for canola.

Fertilizer application rates for camelina were assumed to be 74-22-0-17 kg/ha for N-P-K-S respectively (Saskatchewan Agriculture, 2019). The N application rate corroborates with Li and Mupondwa (2016), who reported that recommended N application rates range from 60 to 100 kg/ha, and is not far from Smart Earth Seeds' maximum N requirements of 67 and 100 kg/ha for Brown and Black soil zones respectively (Smart Earth Seeds, 2019).

4.4.4 Types of Synthetic Nitrogen Fertilizer Used

The type of Nitrogen fertilizer applied is provided from the Fertilizer Use Survey for Ontario and Quebec for corn and soybean (Stratus Ag Research, 2016) For all other regions and other crops, data from Statistics Canada (2016) on fertilizer shipments to provinces (by type) for the July 2014 to June 2015 period was used. These data are not crop-specific. The Statistics Canada data were comparable to the Fertilizer Use Survey data for Ontario and Quebec wheat, and for Alberta barley.

This data category is only provided in the first set of LCI tables (Dataset A1), and not in Dataset A2, because: (1) the fractions from both the Stratus Fertilizer Use surveys and from Statistics Canada do not match up with the fertilizer application rate reported in terms of elemental N, P, K and S; (2) total quantity (by weight, volume, etc.) of fertilizer used was not reported; and (3) they are not needed for calculating N_2O emissions, according to the CRSC method.

Fertilizer type data for canola for RU 23 and 24 in Manitoba, RU 28, 29 and 30 in Saskatchewan, and RU 34, 35 and 37 in Alberta based on the European Commission's canola reports.

4.4.5 Crop Residues

The CRSC reports used values for crop residue mass and nitrogen from Janzen et al. (2003), a Canadian-specific study, and also used averages calculated using Janzen et al., other studies, and IPCC values.

Thiagarajan et al. (2018) updated the values provided by Janzen et al. (2003) for 11 crops in Canada, including wheat, corn, barley, soybean and canola, based on new Canadian-specific references. No distinction was made between wheat and durum wheat. For camelina, generic values for oilseed crops from Fan et al. (2017) were used for the calculation of crop residue mass, and canola values were used for calculating crop residue N.

According to Thiagarajan et al., the partitioning of the total dry matter of a plant into belowground residue (BGR), seed mass (G), and aboveground residue (AGR) is dependent on the seed yield (Y), which is also understood as G over area. The AGR for grain crops is often estimated using the harvest index (HI), which refers to the ratio of seed mass (G) to total shoot mass (G + AGR). The BGR is frequently estimated from shoot mass based on the root/shoot ratios (RSR) based on the entire rooting depth. These values were used to calculate Crop Residue N.

Mass above ground

The crop residue mass above ground in the CRSC Carbon Footprint reports is $\frac{AGR}{G}$.

From Thiagarajan et al. (2018), $= \frac{G}{G+AGR}$. Rearranging, $\frac{AGR}{G} = \frac{1}{HI} - 1.$

It had been previously shown that there is a linear relationship between HI and Y, i.e. $HI = I_c + S_c * Y$, where I_c is the intercept and S_c is the slope of the harvest index-yield relationship. Slopes and intercepts are provided for each crop.

Rearranging, $\frac{AGR}{G} = \frac{1}{I_c + S_c * Y} - 1$

Since yield is RU-specific, RU-specific values for crop residue mass above ground were calculated for the LCI tables.

It must be noted that these values are on the basis of G, which is dry grain or seed mass. To be functionally equivalent with the rest of the data based on the functional unit (see Scope), crop residue mass above ground is multiplied by weight percent of dry grain or oilseed in the total weight of the grain or oilseed inclusive of moisture content. This was done for the aggregated and production weighted set of LCIs (Dataset A2).

Mass below ground

The crop residue mass below ground in the CRSC Carbon Footprint reports is $\frac{BGR}{G}$

Thiagarajan et al. (2018) provided three equations for dry matter partitions, including $BGR(in\ kg/tonne) = \frac{RSR*Y}{I_c+S_c*Y}$, where RSR is the root/shoot ratio.

This can be adapted into a ratio:

$$\frac{BGR}{G} = \frac{RSR}{I_c + S_c * Y}$$

RSR values were provided for each crop.

Since yield is RU-specific, RU-specific values for crop residue mass below ground were calculated.

Crop residue mass below ground was also calculated to be functionally equivalent (per tonne of moist grain or oilseed) with the rest of the inventory data for the second set of LCIs (Dataset A2).

Nitrogen concentrations

Nitrogen concentrations of above and below ground crop residues were updated for each crop in Thiagarajan et al. (2018) on the basis of dry matter. It is expected that N content per dry matter would not change across regions, hence Canada-specific data are sufficient, and RU-specific Crop Residue N can be determined. Mean values are reported in the LCI tables.

There are two exceptions. The below ground Nitrogen value for soybean still uses the values from Janzen et al. (2003) because no update was provided in Thiagarajan et al. (2018). Values intended for canola were used for camelina, since both are oilseed crops and are produced in a similar manner.

4.4.6 Pesticide application rate

Pesticide application rates for canola have been updated with RU-specific data for RU 23 and 24 in Manitoba, RU 28, 29 and 30 in Saskatchewan, and RU 34, 35 and 37 in Alberta based on the European Commission's canola report, which was based on data from the 2011 Canola Council survey. The value of 0.80 a.i. kg / ha was used for the other RUs, according to the CRSC Methodology Report.

From the CRSC reports, actual pesticide application rate was only available for Ontario from a 2014 pesticide survey (Farm & Food Care Ontario, 2015), and for Quebec wheat from Group Ageco (2015). The USDA NASS (2015) data was used for durum wheat. The USDA (n.d.) ARMS survey was consulted for barley. Application rates for the other provinces and other crops are based on the assumption that they were the same as the provinces with data available.

For camelina, the Saskatchewan Crop Planning Guides from 2017 to 2019 recommends the Assure II herbicide and seeding early onto a clean field for pest control. Most producers use about 0.3L/ac of Assure II, (Smart Earth Seeds, 2019), which has an active ingredient concentration of 96 g/L (E.I. du Pont Company, 2016). In addition, most producers also use the Roundup WeatherMax for pre-harvest aid at 0.68L/ac due to the pre-seed burn-off of the active ingredient glyphosate (Smart Earth Seeds, 2019), at a concentration of 540g/L (E.I. du Pont Company, 2017), consistent with that used in the Ontario Food & Farm Care Survey. The total pesticide application rate was calculated to be 0.160 kg/ha. The rate for camelina is lower than that for the other crops.

4.4.7 Direct Energy Use

Energy is used for cultivation, irrigation, trucking, and storage.

According to the CRSC Carbon Footprint Methodology, the cultivation energy for the Prairie Provinces for wheat, durum wheat, barley and canola was calculated from the Prairie Crop Energy Model (PCEM) model, and tillage data is from the 2011 Agricultural census. Cultivation fuel use for non-Prairie provinces were calculated based on tillage practices and typical fuel use values for each type of tillage.

Irrigation energy is included for RUs in Western Canada (BC, Alberta, Saskatchewan and Manitoba) with more than 1% irrigated area. These were RU 35 and 37 in Alberta, and RU 41 and 42 in BC. It was thus assumed that none of the corn and soybean area is irrigated for the purposes of calculating energy use. Therefore, the USDA (2012) ARMS survey data for non-irrigated states were taken for cultivation fuel use for corn and soybeans.

For corn and soybeans, direct energy use was not aggregated because there appeared to be an error in the calculation of aggregated energy use in the CRSC reports, where the per hectare unit for cultivation and the per tonne unit for trucking and storage were conflated. It is likely that the same error was present in the canola energy use summary for Electricity. Steps to correct this error are suggested in a comment on the “Electricity” data category for canola.

Trucking energy use is calculated by using 6.6 MJ/tonne-km of diesel fuel for a mid-size truck, multiplied by an average of 5 km between field and storage bin, to obtain 0.86 litres of diesel per tonne of grain or oilseed.

Storage energy use is calculated by assuming that 0.5 kWh/tonne of electricity is used for moving grain from a truck into a bin and then back into a truck, and another 2 kWh/tonne of electricity is used for aeration of the storage bin.

The European Commission’s canola report provides detailed diesel fuel use calculations and data for canola. The values were similar to the values from the CRSC Canola Carbon Footprint report. The latter was used for the LCI tables for methodological consistency.

Energy use values for natural gas and gasoline were frequently zero when irrigation energy use was not considered, and values for liquid petroleum gas (LPG) was only reported for soybean. Data categories with zero values from the CRSC Carbon Footprint reports, such as LPG, were removed, to distinguish lack of reporting from when reported values are zero.

Direct energy use was not provided in Li & Mupondwa (2014)’s camelina cultivation life cycle inventory. The values for canola were used for camelina, since both are oilseed crops and are produced in a similar manner.

4.4.8 Nitrogen Rates

Nitrogen rates were retotaled to reflect the change in Crop Residue N based on more recent data. These values were used to calculate N_2O emissions in the section N_2O Emissions.

Synthetic N

Synthetic N rates can be calculated by converting the N fertilizer application rate from a per hectare basis to a per tonne basis.

Crop Residue N

Crop Residue N refers to the Nitrogen emissions from the decomposition of the remaining plant matter left on the field after a crop is harvested. The following equation for the amount of nitrogen contained in crop residue on a per tonne basis was derived from matching the mass and nitrogen concentration values for aboveground and belowground biomass (the data provided under the data category Crop Residues) with the Crop Residue N values in the individual CRSC crop reports.

$$\left(\frac{AGR}{G} * above\ ground\ N + \frac{BGR}{G} * below\ ground\ N\right) * \%\ dry\ matter$$

AGR refers to the above ground crop residue, and BGR the below ground crop residue, and both were given on the basis of dry grain or seed in the first set of LCI tables (Dataset A1). This results in RU-specific crop residue N values, since it is expected that N content per dry matter would not change across regions. Finally, the g_N / kg_{grain} unit obtained from the multiplication can be assumed to scale up directly to $kg_N / tonne_{grain}$.

Calculating using this equation and the old Crop Residue values in the CRSC reports produces values that match the Crop Residue N reported in the CRSC reports to ±0.1 kg/tonne for corn, wheat, barley, and canola. There are two exceptions, for which the calculation produced different results: durum wheat and soybean.

For durum wheat, we think that the difference is due to a miscalculation, whereby the % dry matter of wheat was used instead of the % dry matter of durum wheat.

For soybean, we were unable to determine how Crop Residue N was calculated, hence have left the value as 22.7 kg/tonne, extracted from the CRSC Barley Carbon Footprint report, for all RUs.

The final nitrogen rates were retotaled based on these changes.

Soil mineralization N

A default C:N ratio of 10:1 is used to calculate the mineralized N from the soil C, consistent with IPCC guidelines. No further explanation was provided on how mineralized N was calculated.

From the inventory tables, it can be computed that the ratio of total SOC change to soil mineralization N is consistently between 36 and 37 for all RUs, except for those in the Prairies, where soil mineralization N is always zero.

Hence, for camelina, since all production is in the Prairie provinces, soil mineralization N is always zero.

4.4.9 N_2O Emissions

Calculations for N_2O emissions (direct and indirect) were completed using the methodology described in the CRSC Carbon Footprint Methodology Report as follows.

Direct

Direct N_2O emissions were calculated using the Canadian Tier 2 Methodology, excluding manure, and the Emission Factor 1 was modified by AAFC to include adjustments for tillage type, topography, irrigation practices. The formula used is:

$$N2O = (F_{SN} + F_{CR} + F_{SOM}) * EF1$$

where

N_2O = annual direct N_2O–N emissions from N inputs to managed soils, kg $_{N2O–N}$ / yr

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg $_{N}$ / yr

F_{CR} = annual amount of N in crop residues (above-ground and below-ground), returned to soils, kg $_{N}$ / yr

F_{SOM} = annual amount of N in mineral soils that is mineralized, in association with loss of soil C from soil organic matter as a result of changes to land use or management, kg $_{N}$ / yr

EF_1 = Emission Factor 1, kg $_{N2O-N}$ / kg $_{N}$

The N rates in the brackets sum up to “Total N”, which was used for the calculations.

Indirect, volatilization

Indirect N_2O emissions from volatilization follow the Tier 1 Methodology from the IPCC GHG Guidelines (2006) and do not use Canada-specific values. Manure was excluded. The formula used is:

$$N2O_{(ATD)} = (F_{SN} * Frac_{GASF}) * EF4$$

where

$N_2O_{(ATD)}$ = annual amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils, kg $_{N2O–N}$ / yr

$Frac_{GASF}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx, unitless or kg $_{N\ volatilized}$ / kg $_{N\ applied}$ **= <u>0.10</u>**

EF_4 = Emission factor 4 for N_2O emissions from atmospheric deposition of N on soils and water surfaces, unitless or [kg$_{N2O–N}$ (kg $_{NH3–N\ +\ NOx–N\ volatilised}$)$^{-1}$] **= <u>0.01</u>**

Indirect, leached

A modified Canadian Tier 1 Methodology was used to determine indirect leached N_2O emissions. Manure was excluded. The formula used is:

$$N2O_{(L)} = (F_{SN} + F_{CR} + F_{SOM}) * Frac_{LEACH} * EF5$$

where

$N_2O_{(L)}$ = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg $_{N2O–N}$ / yr

$Frac_{LEACH}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, unitless or [kg_{N} / $kg_{N\ additions}$].

EF_5 = Emission factor 5 for N_2O emissions from N leaching and runoff, unitless or [$kg_{N2O–N}$ / $kg_{N\ leached\ and\ runoff}$] = **0.0075**

4.4.10 Soil Organic Carbon Changes

Soil organic carbon (SOC) changes were calculate for management activity changes on cropland remaining cropland. There are three potential sources of SOC change to consider in this context:

1. Mineral soil management practices resulting in reductions in carbon losses, or in some cases a sink, include:
    a. Reducing summer fallow
    b. Increasing no till and reduced till
    c. Reestablishment of perennial vegetation
    d. Yield promoting practices
    e. Irrigation
    f. Manure application
    g. Fertilization
2. CO_2 emissions from cultivation of organic soils.
3. CO_2 emissions and removals from changes in woody biomass from specialty crops.

Only (a) reducing summer fallow, (b) increasing conservation tillage practices, and (c) reestablishment of perennial vegetation were included in the CRSC calculations. Supporting information was not provided in the CRSC methodology report.

The annual change in soil carbon from conventional practices resulting from changes in tillage practices, reduced summer fallow, and the change from perennials to annual crops, as calculated by AAFC for each of the RUs, is reported and utilized on a per hectare basis, up to the 2014 crop year. Similar to the lost carbon from conventional practices, these values are taken as crop-agnostic in the CRSC calculations and in this study.

Both Datasets A1 and A2 show these values on a per tonne basis for each crop in each area (RU for Dataset A1, province for Dataset A2) of production based on yield.

4.5 Data Gaps and Uncertainty in the Agricultural LCI

Little information is available in the CRSC Carbon Footprint reports on variability. Spread was occasionally provided for individual data points. For example, a range of values was reported in the CRSC Barley Carbon Footprint report for seeding rates per RU in Saskatchewan, to reflect the different values for feed and malting barley.

Variability was reported in the updated values for the mass and nitrogen concentration of crop residues from Thiagarajan et al. (2018) and Fan et al. (2017). Mean values were used for the data points.

Spatial variability is seen between RUs and provinces, which is what these inventories aim to show. There would also be spatial variability within an RU, but this was not reflected. To minimize temporal variability, the CRSC reports attempted to use data that is recent and from a similar time period. Variability between objects was said to have little consequence on the CRSC studies.

The treatment of Soil Organic Carbon (SOC) relied on an approximation that the annual change in soil carbon resulting from changes in tillage practices, reduced summer fallow, and the change from perennials to annual crops could be treated as the same for each crop type in each RU. There is a high degree of both variability and uncertainty associated with SOC changes from agricultural land transformation. Additional research is needed to better associate these processes with specific crops and decrease their overall uncertainty.

In the CRSC methodology report, data quality was assessed to be “quite good” for crop yields and fertilizer application rates, “not as good” for direct energy use, and “poor” for pesticide application rates.

4.6 Agrochemicals upstream emissions

As described above, the CALDC library has N, P, K and S nutrient use, as well as pesticide application rates, as extracted from the CRSC reports and related sources. The CI values for N, P and K nutrients from Canadian fertilizers have been taken from a fertilizers report prepared for the CRSC analysis (Cheminfo , 2016), based on 2014 market data and detailed producer data. S nutrient and pesticide CI values from detailed LCI data for fertilizer and pesticide inputs are taken from the GREET2018 model (ANL, 2018).

There are five primary pesticides in widespread use for the relevant crops. In the absence of detailed data in the LCI as to the share of each type used on a given crop or the data analogous to that for Canadian fertilizer shipments to agriculture, the upstream emissions for pesticides are treated as an average of the emissions for each of the five pesticides.

Table 4 shows the nutrient and pesticide CIs used for the crop-based low carbon fuel pathways.

Table 4: Nutrient and pesticide cradle-to-farm emissions used in the pathways, in grams per kg.

Input				**CO_2 eq.**
N, per kg				3,180
P, per kg				930
K, per kg				278
	CH_4	**N_2O**	**CO_2**	**CO_2eq**
S, per kg	8.51	0.056	2,829.6	3,083
Pesticide, per kg a.i.	32.32	0.329	18,820	19,880

As the Canadian-specific report (Cheminfo , 2016) has only the aggregated CO2eq values, a separate set of processes have been developed to make the individual CH_4, N_2O and CO_2 contributions available; this is based on 2014-2017 market data (Statistics Canada, 2019), nutrient balances, and individual contributions for each fertilizer from the GREET2018 LCI; these values can be found in Table 112, Table 111, and Table 113 in Appendix section 0 A1. Agrochemicals Carbon Intensity Data.

4.7 Carbon Intensity values for Crops

4.7.1 Key LCI data

Management practice LCI data for relevant grain crops and oilseed crops are summarized in Table 5 and Table 6, respectively. Table 7 provides a summary of energy inputs to crop cultivation and management.

Table 5: Grain crop management practice data per tonne of harvested crop (dry matter basis as compiled for the CALDC Agricultural LCIs based on the CRSC reports and other sources.

Province	Production Data			Seeding Rates	Fertilizer application rate				Pesticide application rate
	Harvest Area, ha	Production, T	Yield, T/ha	kg/T	N, kg/T	P, kg/T	K, kg/T	S, kg/T	Active Ingredient kg/T
Corn									
NS	13,600	101,467	7.46	2.68	20.00	5.006	5.006	1.001	0.26
PE					20.00	4.996	4.996	1.004	
NB					20.00	4.994	4.994	0.993	
PQ	381,865	3,429,257	8.9803	2.38	16.40	5.101	5.101	0.499	
ON	846,727	8,398,858	9.9192	2.15	14.20	4.327	6.934	0.701	
MB	137,889	1,005,621	7.2930	3	17.64	5.229	3.463	1.166	
Wheat									
NS	13,701	46,934	3.43	33.6	21.84	6.794	1.941	0.971	0.20
PE					27.02	8.407	2.402	1.201	
NB					29.34	9.129	2.608	1.304	
PQ	52,491	170,909	3.2560	58.4	13.4	2.9	6.91	0.28	0.25
ON	385,759	1,995,152	5.1720	24.2	21.1	7.0	4.76	2.20	0.13
MB	1,196,583	4,193,901	3.5049	5.3	27.2	10.0	2.43	1.16	0.20
SK	3,735,009	10,508,747	2.8136	114.4	26.9	9.5	1.19	1.56	0.25
AB	2,244,640	7,967,484	3.5496	32.4	27.2	6.6	2.82	0.74	0.20
BC	13,084	43,729	3.3422	34.4	26.9	8.4	2.39	1.20	0.21
Barley									
NS	37,266	119,867	3.22	34.2	24.2	8.1	3.2	1.61	0.30
PE					22.7	7.6	3.0	1.52	
NB					25.3	8.4	3.4	1.69	
PQ	59,366	190,275	3.2051	53.0	24.3	14.7	10.92	1.56	
ON	39,902	136,554	3.4222	39.2	22.8	8.8	6.72	1.46	

MB	158,771	554,723	3.4939	30.6	23.3	9.5	2.41	1.16	
SK	844,085	2,477,764	2.9354	123.5	24.3	9.2	1.60	1.38	
AB	1,097,281	4,001,527	3.6468	30.2	22.4	8.3	2.16	1.95	
BC	9,113	29,156	3.1994	34.4	23.4	7.8	3.13	1.56	

Table 6: Oilseed crop management data per tonne of harvested crop (dry matter basis), as compiled for the CALDC Agricultural LCIs based on the CRSC reports and other sources.

Province	**Production Data**			**Seeding Rates**	**Fertilizer application rate**				**Pesticide application rate**
	Harvest Area, ha	Production, T	Yield, T/ha	kg/tonne	N, kg/T	P, kg/T	K, kg/T	S, kg/T	Active Ingredient kg/T
Canola									
NB	2,200	4,633	2.106	2.659	47	14	3.8	7.1	0.42
MB	1,272,119	2,397,762	1.885	8.8	57	18	4.0	9.3	
SK	4,112,144	7,261,064	1.766	9.3	54	16	1.7	9.8	
AB	2,247,367	4,856,114	2.161	7.7	45	14	7.9	8.8	
BC	16,305	30,799	1.889	8.9	47	16	4.2	7.9	
Soybean									
NS	33,300	82,167	2.47	26.5	2.04	5.433	11.884	0.306	0.61
PE					2.46	6.548	14.324	0.368	
NB					2.73	7.269	15.902	0.409	
PQ	301,381	856,246	2.841	26.4	2.64	2.957	4.681	0.317	
ON	1,109,257	3,472,397	3.130	22.4	1.66	4.934	13.793	0.231	
MB	295,625	694,737	2.350	34	1.85	13.643	5.937	1.213	
Camelina									
MB	304	510	1.7	4.0	44	13	0	10	0.16
SK	2,221	2,506	1.13	5.9	66	19	0	15	0.16

One of the objectives for the Fuel LCA Modelling Tool is to be able to reflect regional or provincial differences in carbon intensity for low carbon fuels. The provincial-level LCI data in the CALCD accommodate this.

Table 7. Agricultural energy use data per tonne of harvested crop (dry matter basis) for grain crops, as compiled for the CALDC Agricultural LCIs based on the CRSC reports and other sources.

Province	Direct Energy Use for Cultivation (on-farm)					Energy Use for Storage	Energy Use for Trucking
	Diesel, L/tonne	Gasoline, L/tonne	Natural gas, MJ/tonne	LPG, L/tonne	Electricity, kWh/tonne	Electricity, kWh/tonne	Diesel, L/tonne
Corn							
NS	3.99	1.9	7.04	2.0	1.9	2.5	0.86
PE							
NB							
PQ							
ON							
MB							
Wheat							
NS	7.9	0.0	0.0	0.0	0.61	2.5	0.86
PE	9.8	0.0	0.0	0.0	0.75		
NB	10.6	0.0	0.0	0.0	0.82		
PQ	10.5	0.0	0.0	0.0	34.0		
ON	6.5	0.0	0.0	0.0	37.6		
MB	9.8	0.0	0.0	0.0	39.3		
SK	9.5	0.0	0.0	0.0	39.0		
AB	8.9	0.0	0.0	0.0	39.4		
BC	8.0	0.0	0.0	0.0	40.0		
Barley							
NS	32.6	0.0	0.0	0.0	0.0	2.5	0.86
PE	32.6	0.0	0.0	0.0	0.0		
NB	32.6	0.0	0.0	0.0	0.0		
PQ	34.3	0.0	0.0	0.0	0.0		
ON	33.8	0.0	0.0	0.0	0.0		
MB	37.8	0.0	0.0	0.0	0.0		
SK	29.6	0.0	0.0	0.0	0.0		
AB	30.7	0.0	0.0	0.0	0.0		
BC	28.5	0.0	0.0	0.0	0.0		

Table 8. Agricultural energy use data per tonne of harvested crop (dry matter basis), for oilseed crops, as compiled for the CALDC Agricultural LCIs based on the CRSC reports and other sources.

Province	Direct Energy Use for Cultivation (on-farm)					Energy Use for Storage	Energy Use for Trucking
	Diesel, L/tonne	Gasoline, L/tonne	Natural gas, MJ/tonne	LPG, L/tonne	Electricity, kWh/tonne	Electricity, kWh/tonne	Diesel, L/tonne
Soybean							
NS	9.00	3.34	0.0	0.03	3.00	2.5	0.86
PE							
NB							
PQ							
ON							
MB							
Canola							
NB	15.5	0.0	0.0	0.0	1.2	2.5	0.86
MB	18.4	0.0	0.0	0.0	1.3		
SK	15.2	0.0	0.0	0.0	1.4		
AB	13.5	0.0	24.0	0.0	4.4		
BC	15.7	0.1	128.8	0.0	18.8		
Camelina							
MB	20					2.5	0.86
SK	22.6					2.5	0.86

Peas are not yet included in the CALDC LCI dataset, so the Canadian Agricultural summary value (0.38 kg CO_2 eq./kg dry matter) has been used (Desjardins, et al., 2016).

4.7.2 Calculated CI values for crop production

Canadian average and provincial CIs for the included crops are presented in Table 9. The results of the uncertainty analysis on Canadian average production for these crops are shown in Table 11.

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Table 9. Provincial and Canadian average (production weighted) carbon intensity values (cradle to gate) including SOC contributions for key crop feedstocks, expressed in g CO_2 eq./kg of crop produced (dry matter basis), shown with CRSC reported values (previously cited reports; values with "~" are estimated from Churchill & O'Connor 2017).

	Grain Crops					Oilseed Crops		
CI (g CO_2eq/kg)	**Corn**	**Wheat**	**Durum Wheat**	**Barley**	**Dry Peas***	**Canola**	**Soybean**	**Camelina****
Canada Average	350	180	75	150	380	380	410	-
Alberta	-	170	440	130		390	-	-
British Columbia	-	310	-	420	-	620	-	-
Manitoba	180	240	-	210		580	20	390
New Brunswick	480	780	-	740	-	1,300	580	-
Nova Scotia	650	980	-	1,200	-	-	950	-
Ontario	340	530	-	680	-	-	430	-
Prince Edward Island	460	770	-	720	-	-	570	-
Quebec	440	690	-	820	-	-	610	-
Saskatchewan	-	79	30	72		310	-	140
CRSC Canada Average	370	230	~80	196		383	~580	

* Dry peas value from Desjardins et al 2018. **Because there is so little camelina produced in Canada currently, almost all in Saskatchewan, a Canadian average value is not calculated.

For grain crops, the production impacts in all provinces and at the national level are driven by nutrient use and SOC changes with land conversion. For canola and camelina, nutrients use and SOC changes dominate, and for soybeans, the pesticide use contribution is about equivalent with that of nutrients use. Higher CIs in Manitoba and New Brunswick, particularly for canola (NB) and barley (MB), are driven by higher N2O emissions and net soil carbon loss. These are consistent with the large variation in net GHG emissions reported as part of the CRSC effort.

Results for Canadian average crops are in good agreement with the CRSC analysis. Differences between the current analysis and CRSC values are generally due to differences in upstream processes. While the inventory data is primarily derived from the CRSC reports as described above, upstream processes differ in some cases. In particular, we have updated the analysis using the 2016 grid electricity model year in place of 2014, and all fuels use the pathways developed during Milestone 2. Additionally, we have augmented the N, P, K nutrient emissions with processes for pesticides and S nutrients.

Because SOC values are more speculative, CI values without SOC are shown in Table 10.

Table 10. Provincial and Canadian average (production weighted) carbon intensity values (cradle-to-gate) *excluding* SOC contributions for key crop feedstocks, expressed in g CO_2 eq./kg of crop produced (dry matter basis).

	Grain Crops					Oilseed Crops		
CI (g CO_2eq/kg)	Corn	Wheat	Durum Wheat	Barley	Dry Peas*	Canola	Soybean	Camelina**
Canada Average	270	300	250	270	*380*	610	160	-
Alberta	-	300	320	250	-	580	-	-
British Columbia	-	340	-	350		660	-	-
Manitoba	210	300	-	280	-	710	110	530
New Brunswick	370	540	-	490		980	240	-
Nova Scotia	400	490	-	570		-	280	-
Ontario	250	370	-	420		-	160	-
Prince Edward Island	360	510	-	460		-	230	-
Quebec	310	360	-	500	-	-	210	-
Saskatchewan	-	270	240	260		600	-	630

* Dry peas value from Desjardins et al 2018. **Because there is so little camelina produced in Canada currently, almost all in Saskatchewan, a Canadian average value is not calculated.

4.7.3 Data quality and uncertainty in crop production CIs

Table 11 presents the results of the uncertainty analysis on for the CI of Canadian average production for each crop. Where possible, the range is based on minimum and maximum values from provincial values, in preference to a pedigree matrix.

The results show a high degree of uncertainty, which is typical of agricultural systems, and reflect the extent of variation amongst provinces. This differs from the average values in Table 9, which are production weighted and thus reflect most probable values.

The lower bound of the 95% confidence level (2.50%) suggests other significant factors beyond expected agricultural process variation. The negative values are a result to the dominant SOC values. Figure 3 explores this more detail, showing the total (left) and the SOC contribution (right).

Table 11: Results of uncertainty analysis on crop production cradle-to-gate CIs in the CALDC library.

Crop	Mean	Median	Standard Deviation	2.50%	97.50%	Standard Error of the Mean	Unit
Grain Crops							
Corn	410	390	140	230	730	3.2	g CO_2 eq/kg
Wheat	530	490	240	200	1,200	5.4	g CO_2 eq/kg
Durum Wheat	170	150	160	-90	550	3.6	g CO_2 eq/kg
Barley	670	620	280	260	1,400	6.3	g CO_2 eq/kg
Oilseed Crops							
Canola	460	470	180	77	780	3.9	g CO_2 eq/kg
Camelina (SK)	490	400	330	130	1,400	7.3	g CO_2 eq/kg
Soybean	150	160	400	-720	910	8.9	g CO_2 eq/kg

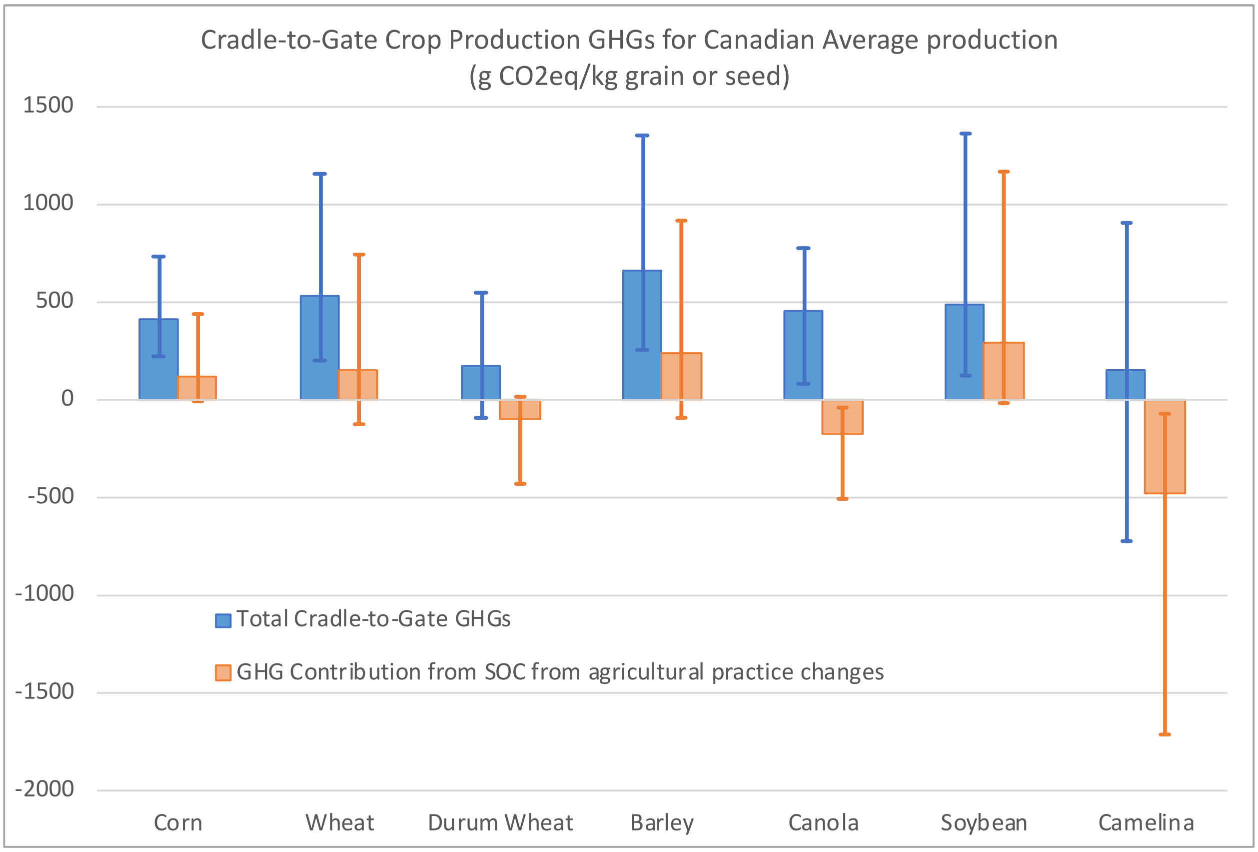

Figure 3: Carbon Intensities Canadian average grain and oilseed crops total (left, blue) and contribution from land transformation (SOC) (right, orange), showing significance of SOC uncertainty.

Figure 3 shows CI results with uncertainty for Canadian average crops. They exhibit high uncertainty and a significant contribution from soil organic carbon arising from changes in management practice. It illustrates the challenge of incorporating management practice change land transformation values as well as underlying data gaps. As discussed above, the approximation the annual change in soil carbon resulting from changes in tillage practices, reduced summer fallow, and the change from perennials to annual crops is the same for all crops compounds the already high uncertainty (the CRSC study classified emissions data quality as “poor”) with potentially misleading estimates for SOC changes for some crops. The net result is an extremely high uncertainty at the provincial and national level for GHGs from land transformation and for total crop GHGs (see Figure 3).

4.7.4 Data Gaps for Crop Production CIs

- Soil organic carbon approximations. There is a high degree of uncertainty associated with SOC changes from agricultural land transformation already; by not applying any production weighting for crops produced in a given RU or province, that uncertainty is compounded and, in some cases, results in unexpected negative emissions. Additional research is needed to better associate these processes with specific crops and decrease their overall uncertainty.
- Canola in Ontario (and data for other small contributors to various crops)

4.8 Carbon Intensity values for crop residues

Collecting and removing crop residues adds additional energy use and nutrient replacement above conventional crop production, as well as potential water use and emissions changes. Crop residues thus differ from a simple waste and require an independent Carbon Intensity value. Through discussions with ECCC, it was decided that in the interests of transparency, and to avoid allocation, a highly simplified crop residue process is used. This approach is described below.

4.8.1 Approach Summary

Current practice in Canada, to which the CSRC data relates, has minimal residue collection and negligible amounts used for bioenergy. Residue collection is therefore treated as a collection of practices additional to that data. A CI for residues is developed based on 1) replacement of N in collected residues assuming application of equivalent amounts of nutrient; and 2) a coarse estimate for diesel use in collection of residues as an additional harvesting pass over the fields. This is calculated per tonne of collected biomass. Together these provide a rough estimate to contribute to the CI of crop residues for use in bioenergy production.

Removal of residues can also change yields, water demand, demand for nutrients other than N, and field emissions; however, these processes are more complex and uncertain than can be accommodated here and are omitted from the CI. The uncertainty on the CI reflects these assumptions.

The approach used here ensures the residues carry a non-zero impact that can be clearly related back to the quantity of residue used. For example, if a given producer decides that they are working with a farmer and collecting, e.g., 30% of the crop residue in those fields, the calculated CI will give a coarse sense for it. Future work is anticipated to refine the handling of crop residues in the Tool. The approach here is intentionally over-simplified, with the expectation that it will provided an initial, transparent, framework for future modelers.

Nutrient Replacement and Biomass Yield

Residues carry a non-zero impact that can be clearly related back to the quantity of residue used. For example, if a given producer decides that they are working with a farmer and collecting, e.g., 30% of the crop residue in those fields, the calculated CI will give a coarse sense for it. Future work is anticipated to refine the handling of crop residues in the Tool.

The quantity of N removed from the field in collected biomass is calculated using the N content in Table 12 and the biomass yields from CRSC data. The content of other nutrients and micronutrients in crop biomass are not included in the CRSC data.

Table 12: Nitrogen content in above ground biomass for cellulosic ethanol feedstocks used here, in kg N per tonne dry matter (residue) (Thiagarajan et al 2018), used for calculating the nutrient replacement contribution to the crop residue Carbon Intensity.

	Mean	Standard Deviation	Unit
Wheat straw	6.64	3.15	kg N/t Dry Matter
Corn stover	9.37	2.59	kg N/t Dry Matter

To account for the fact that only a portion of the N in the harvest residues is available to the crop, a range of 0% to 72% with a peak of 58% is applied. The Canadian average CI for nutrient N is then used to calculate the impact of replacing the removed nutrient.

Energy Use

The vehicle and diesel use in residue collection is treated as an additional transportation impact, using a simple heavy-duty diesel truck as a proxy. Distance is estimated based on per hectare yields, assuming a square field, and the number of passes to cover the field with average grain combine harvester head sizes[4].

To collect residues uniformly across the entire field, these averages give rise to travel distances between 0.8 and 1.9 km per ha, with an average of 1.1 km/ha. Calculated distances for collection are shown in Table 13 with their underlying yields.

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[4] Cutting widths, compiled from grain combine harvester comparison charts at https://www.caseih.com/northamerica/en-us/Pages/Comparison.aspx?family=GrainHeadsRigidCombine#, generally range from 5.2m to 12.5m, with an average of 8.9m; the width offered by the greatest number of manufactures is 9.14m.

Table 13: Canadian provincial and national average crop residue yields and generalized collection distance for wheat straw and corn stover used for estimating the residue collection contribution Carbon Intensity.

Province	Crop residues yield (mass), tonne biomass (dry)/ha			Average distance covered for collection, km per tonne biomass (dry)		
	Corn Stover	Wheat Straw, non-Durum	Wheat Straw, Durum	Corn Stover	Wheat Straw, non-Durum	Wheat Straw, Durum
Nova Scotia	7.000	4.428		0.161	0.254	
Prince Edward Island	7.224	3.247		0.156	0.347	
New Brunswick	6.501	2.866		0.173	0.393	
Quebec	7.560	4.464		0.149	0.252	
Ontario	7.894	5.485		0.143	0.205	
Manitoba	6.795	3.103		0.166	0.363	
Saskatchewan		2.562			0.440	
Alberta		3.863	3.957		0.292	0.285
British Columbia		3.265	3.825		0.345	0.294
National Average, Production Weighted	7.712	3.319	3.936	0.146	0.359	0.286

4.8.2 Calculated Carbon Intensity Values for Crop Residues

The following tables show the provincial and national average CIs for the feedstock contribution to the crop residue cellulosic ethanol pathways. Table 14 shows the CI for corn stover, and Table 15 that for wheat straw. Table 16 presents the results of the uncertainty analysis for corn stover and wheat straw.

Table 14: Provincial and national average (production weighted) Carbon Intensity values for corn stover from collection, replacing N removed in the collected biomass, and the combined total, in kg CO2eq/tonne (dry matter).

Province	Collection, kg CO2eq/tonne (dry matter)	replacement (58%), kg CO2eq/tonne (dry matter)	Combined kg CO2eq/tonne (dry matter)
Nova Scotia	0.022	17.28	17.304
Prince Edward Island	0.022	17.28	17.304
New Brunswick	0.024	17.28	17.306
Quebec	0.021	17.28	17.303
Ontario	0.020	17.28	17.302
Manitoba	0.023	17.28	17.305
National Average, Production Weighted	0.020	17.28	17.302

Table 15: Provincial and national average (production weighted) Carbon Intensity values for wheat straw (Durum and non-Durum varieties) from collection, replacing N removed in the collected biomass, and the combined total, in kg CO2eq/tonne (dry matter).

	Wheat straw, non-Durum			Wheat straw, Durum		
Province	Collection	58% N replacement	Combined	Collection	58% N replacement	Combined
Nova Scotia	0.035	12.2	12.282			
Prince Edward Island	0.048	12.2	12.295			
New Brunswick	0.054	12.2	12.301			
Quebec	0.035	12.2	12.282			
Ontario	0.028	12.2	12.275			
Manitoba	0.050	12.2	12.297			
Saskatchewan	0.061	12.2	12.308			
Alberta	0.040	12.2	12.287	0.039	12.2	12.286
British Columbia	0.048	12.2	12.295	0.041	12.2	12.288
National Average, Production Weighted	0.050	12.2	12.297	0.040	12.2	12.287

4.8.3 Uncertainty Analysis of Crop Residue CIs

The agricultural residue CIs are more speculative than the crop production CIs. Because they are currently a residue of crop production rather than a co-product, they do not carry any of the grain/primary crop production impacts (i.e., they are not an allocated process). However, there are impacts specifically associated with the collection and removal of these residues. Data specific to these practices are not available, so simplified processes were created for the residues, as described in Section. 4.8.

CIs range from nearly zero to 20-30 g CO_2 eq/kg dry matter, driven by the wide uncertainty around how much of the nutrient in the biomass residue removed would have been available for the crop and thus must be replaced (0-72%). Energy use for the passes over the field to collect the biomass make a much smaller contribution.

Table 16: Results of uncertainty analysis on crop residue CIs.

Biomass	Mean	Median	Standard Deviation	2.50%	97.50%	Standard Error of the Mean	Unit
Corn stover	0.0130	0.0113	0.0078	0.0023	0.0330	0.0002	kg CO_2 eq/kg dry matter
Wheat straw, non-Durum	0.0092	0.0079	0.0061	0.0014	0.0246	0.0001	kg CO_2 eq/kg dry matter
Wheat straw, Durum	0.0091	0.0079	0.0059	0.0015	0.0244	0.0001	kg CO_2 eq/kg dry matter

4.8.4 Data Gaps for Agricultural Residues CIs

- Field-level collection fraction response: In an actual implementation, a given project is most likely to involve collection of a fraction of the field's total residues, and research has thus far shown a relationship between field response and share of material collected more complex than the simple linear residue mass: field-level response assumption necessitated here. *Additional research and reporting needed.*
- Residue collection energy use - distance traveled in field, truck vs. harvester or truck and trailer, collection fraction. *Additional reporting and some research needed.*
- Field level yield and nutrient needs response - as each pass over the field can compact soil which may affect yields and removal of residue may alter both nutrient (N and others) and water needs, additional data is needed around yield responses to residue collection. *Additional research and reporting needed.*
- Impact of residue collection on field emissions -- *additional research and reporting needed.*

5. Conventional Crop-Based Low Carbon Liquid Fuels

5.1 System Boundaries and Descriptions for Conventional Crop-based Low Carbon Liquid Fuels

Low Carbon liquid fuels can be produced from a variety of renewable Canadian crops, whether grains (e.g., conventional bioethanol) or oilseeds (e.g., biodiesel), as well as agricultural residues or purpose-grown biomass (lignocellulosic ethanol and advanced biofuels). Lignocellulosic agricultural residues are also used as low carbon liquid fuels. Bioethanol and biodiesel are in commercial production and use and are considered conventional crop-based fuels. All other fuels are considered unconventional within this report. Conventional crop-based liquid fuels are typically blended with their fossil analogues for use in internal combustion engines, although advanced processes to produce drop-in fuels as direct replacements for their fossil analogues are emerging. Low carbon liquid fuels are typically used for transportation of passengers and goods, with some biodiesel also used for heating.

The Canadian crop-based low carbon liquid fuels incorporated in the Fuel LCA Modelling Tool are summarized in Table 17. Cereal grains are used for starch-based ethanol from fermentation, while oilseeds are processed and refined for oil-based fuels. Lignocellulosic residual biomass from these crops, primarily corn stover or wheat straw, may be used after additional processing for ethanol via fermentation[5].

Table 17. Summary of crop-based low carbon liquid fuel pathways including descriptions of fuel feedstock source, conversion processes, process energy carrier outputs, and expected end use to be modelled (feedstocks marked with an asterisk are not modelled in detail here).

Fuel	Feedstock	Conversion Process	End Use
Bioethanol	Grain corn Wheat Barley *Peas**	Starch extraction Liquefication and saccharification Fermentation Ethanol recovery	Transportation
Biodiesel	Canola Soybean Camelina	Oil extraction Transesterification Refining	Transportation (heating)
Lignocellulosic Ethanol	Corn stover Wheat straw	Pretreatment Saccharification Fermentation Ethanol recovery	Transportation

Detailed provincial and anonymized LCI data for Canadian grain bioethanol and Canadian mixed feedstock biodiesel have been compiled by NRCan as part of the NRCan's ecoENERGY for Biofuels Program, which ran between 2008 and 2017 (Natural Resources Canada, 2019). The data is aggregated from information provided in Complementary Environmental Performance Reports (CEPR). While reported data drops sharply from 2016 on, the CEPR data still provides a valuable picture of industry

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[5] Other routes, both biochemical and thermochemical, are also possible, though primarily at research or pilot scales.

average production. This data has been used to develop Canadian average bioethanol and biodiesel pathways. In addition, genericized templates of these have been developed.

5.1.1 Starch Based Fuels

Crop production and use

Canadian agriculture produces a variety of grains that, among their other uses, serve as low carbon fuel feedstocks. The starch they contain is hydrolyzed to sugar (glucose) and thence to bioethanol via fermentation. The conversion of grains to ethanol in industrial plants (also referred to as distilleries) also produce livestock feed and supplements, and, sometimes, other co-products.

The Canadian bioethanol industry is an expanding sector of the economy, producing fuel ethanol for domestic use (US Department of Agriculture, 2018; National Energy Board Canada, 2016). At the end of 2018, there were 15 operational conventional bioethanol plants in Canada, of which 13 are crop-based[6]. A summary of capacity provided by currently operational plants is provided in Table 18.

Canadian bioethanol production is dominated by Ontario, which produces more than 60% of Canada's annual bioethanol, from corn, and Saskatchewan, primarily from wheat, which accounts for about 18%. The remaining 22% comes from Alberta, Manitoba, and Quebec, each of which provide 3-10% of annual production (Ethanol Producer Magazine, 2019).

Table 18. Capacities of operational crop-based bioethanol plants in Canada as of September 2018, shown by location, feedstock, annual capacity in million litres, and co-products (Ethanol Producer Magazine, 2019).

Plant Location	Province	Feedstock	Ethanol Capacity (million L/year)	Co-products
Red Deer	Alberta	Other Grains (primarily wheat, some barley or corn)	45	Wheat flour, Gluten, CO_2, Feed
Minnedosa	Manitoba	Corn	129	Distiller's dried grains with solubles (typically used for feed or food additives, often called DDGS)
Chatham	Ontario	Corn	200*	Industrial alcohols, Corn oil, Livestock feed
Johnston	Ontario	Corn	261	Corn oil, CO_2, Feed
Tiverton	Ontario	Corn	32*	Industrial alcohols, Feed
Aylmer	Ontario	Corn	380	Feed
Havelock	Ontario	Corn	80	Feed
Sarnia	Ontario	Corn	400	Feed
Varenes	Quebec	Corn	174	Corn oil, Feed
Llyodminster	Saskatchewan	Grains (primarily wheat)	129	Feed
Unity	Saskatchewan	Grains (primarily wheat, some barley)	25	Industrial ethanol, Feed

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[6] The others are based on waste, covered elsewhere.

Lanigan	Saskatchewan	Grains (primarily wheat, some barley or corn)	14	Feed
Belle Plaine	Saskatchewan	Grains (primarily wheat)	151	Feed

* total alcohols

Canadian bioethanol producers use several grain crops to produce ethanol. Table 19 shows the crop volumes produced and used nationally (from (Littlejohns, Rehmann, Murdy, Oo, & Neill, 2018)) along with the share of ethanol production capacity provided by each.

Table 19: Grain crop feedstocks used in 2016 (Littlejohns, Rehmann, Murdy, Oo, & Neill, 2018)

Crop	Seed area (thousand Ha)	Production (MT)	Biofuel use (MT)	CEPR Reported Share of production 2012-16, Eastern Canada*	CEPR Reported Share of production 2012-16, Western Canada*	CEPR Reported Share of national production, 2012-16
Grain corn	1345	13193	3250	100%	4%	97%
Wheat	9420	31729	950		96%	3%
Barley	2586	8784	-	-	-	-
Dry peas	1715	4836	-	-	-	-

* average over 2012-2016, from CEPR data (Natural Resources Canada, 2019)

Table 20 shows national regional ethanol production over 2012-2016 (Natural Resources Canada, 2019). The primary bioethanol feedstocks have been corn and wheat (97% and 3%, respectively, over 2012-2016 according to producer supplied data under ecoEBE (Natural Resources Canada, 2019), as shown in Table 20). Barley and other starches provided small amounts of ethanol. (Both corn stover and wheat straw are being used and explored for lignocellulosic ethanol, as are other agricultural residues; this fuel pathway is described in Section 6).

Table 20: Crop-based bioethanol production in Canada, 2012-2016, in ML (Natural Resources Canada, 2019) from CEPR (ecoEBE) data.

Million L	2012-13	2013-14	2014-15	*2015-16*
Total	1,695	1,703	1,718	*569*
Western Canada	485	489	489	*20*
Eastern Canada	1,210	1,214	1,229	*549*
Share west (%)	29%	29%	28%	*4%*
Share east (%)	71%	71%	72%	*96%*
Share corn (%)	81%	81%	80%	*97%*
Share wheat (%)	19%	19%	20%	*3%*

While changes in production incentives lead to a precipitous drop in participation from mid-2015 on, the CEPR data still provides a valuable picture of average production

Conversion to bioethanol

There are two conversion process types for the production of bioethanol from grains: wet and dry milling. Dry milling is dominant for bioethanol production (Littlejohns, Rehmann, Murdy, Oo, & Neill, 2018), although about 10% of production is via wet milling. The two processes differ primarily in the initial treatment of the grains for starch extraction and the total water use. Both processes are highly integrated in commercial production. The conversion process for grain to ethanol varies little among grain types.

The first part of bioethanol production from grain releases the starch. In dry milling, the grain is ground, mashed and cooked to release the starch. In wet milling, the grain is fractionated by steeping, resulting in germ, gluten, and fibre along with starch. The starch produced undergoes enzymatic hydrolysis to release glucose, a six-carbon sugar, for fermentation by industrial yeast. The fermentation process yields an ethanol- and protein-rich broth sometimes referred to as wine or beer. It also releases CO_2 as the glucose is converted into ethanol. After fermentation, the ethanol is recovered from the broth and dried, first undergoing distillation, then drying over molecular sieves to remove the remaining water from the azeotropic solution, and finally, for fuel ethanol, a denaturant, often a small fraction of gasoline, is added, making it unsuitable for human consumption. The stillage residue post-distillation undergoes further processing to remove water reused in the process and produce wet and/or dry distillers' grains and solubles, widely used in livestock feed.

As mentioned, a highly-integrated conversion process, whether wet or dry milling, yields important co-products – key livestock feeds and feed supplements, and in some cases other alcohols and corn oil. Some facilities also capture the CO_2 resulting from fermentation and compress it for use in beverage and other markets. Table 18 shows the co-products reported by each producer.

The system boundaries and process flow for conventional bioethanol production from grain are summarized in Figure 4.This includes wheat, corn, and some barley, rye or minor contributing grains (grains other than wheat, corn and barley are not included in the inventories).

Fuel Ethanol Combustion

Crop-based low carbon liquid fuels are used overwhelmingly in the transportation sector, either neat (unblended) or blended with their fossil analogues. The emissions from combustion of ethanol depend on efficiency and type of vehicle. As it is not feasible to capture the full range of possible combustion scenarios for the vehicle fleet, in the Fuel LCA Modelling Tool the combustion of crop-based conventional bioethanol will be modelled stoichiometrically and harmonized with the Canadian NIR report. A representative vehicle is used here for each fuel (see Section 5.3.5). However, as the carbon emissions from combustion of crop-based conventional bioethanol are entirely biogenic, they are not included in the carbon intensity for the crop-based conventional bioethanol pathway.

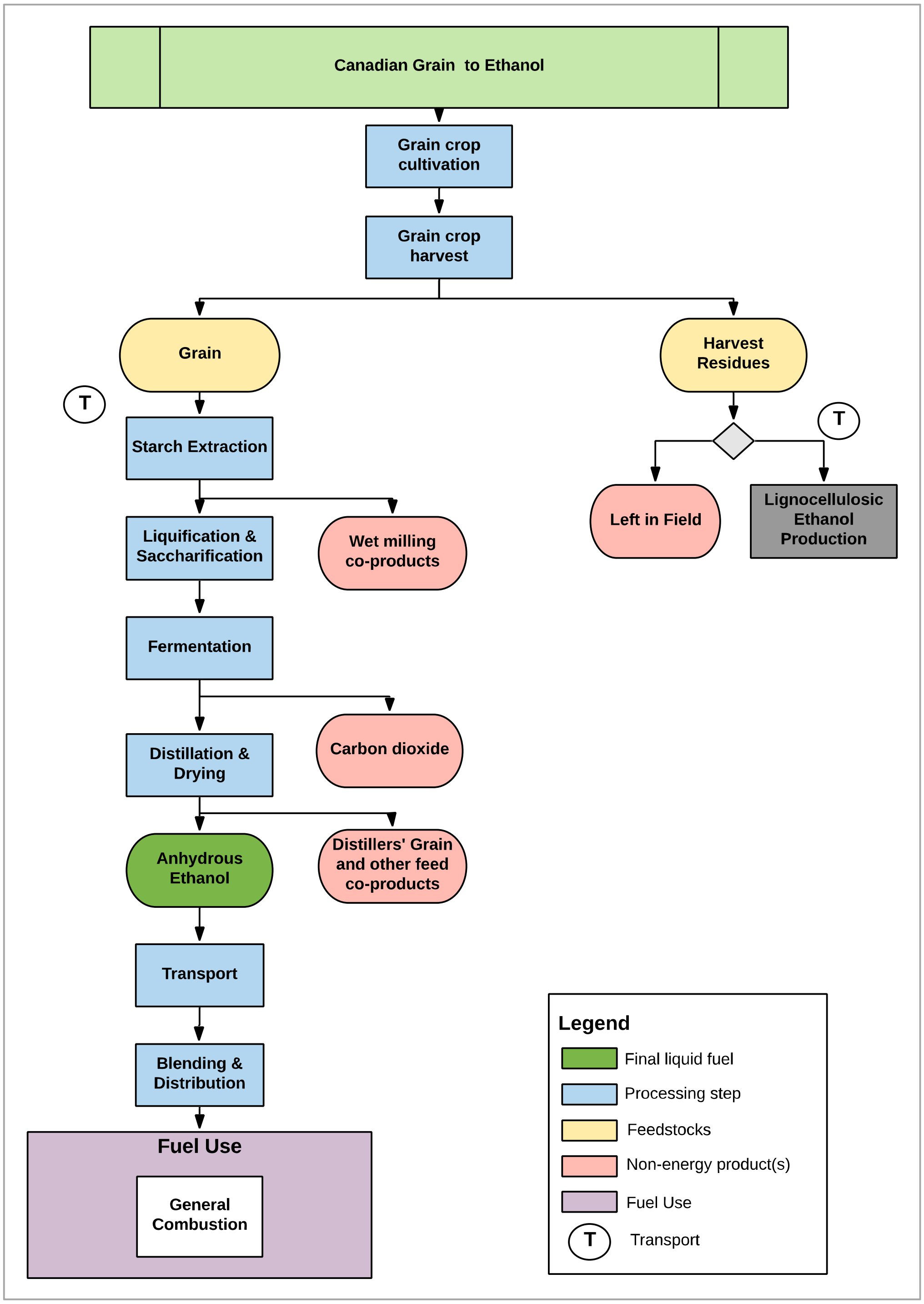

Figure 4. System boundaries and life cycle activities for bioethanol derived from grain crop feedstocks, from cultivation to combustion.

5.1.2 Oilseed Based Fuels

Crop production and use

Canadian agriculture produces a variety of oilseeds that, among their other uses, serve as low carbon fuel feedstocks. The oil they contain is extracted and then chemically converted to biodiesel. The conversion of oilseeds, or oil from oilseeds to biodiesel in industrial plants (also referred to as mills or refineries) also produces protein meal and sometimes, other co-products.

At the end of 2017, there were 10 operational biodiesel plants in Canada, of which four are crop-based[7]. Together, these crop-based facilities accounted for 78% of capacity at that point (Biodiesel Magazine, 2019). Over the last several years, more than 70% of biodiesel produced in Canada has been from edible oils (Littlejohns, Rehmann, Murdy, Oo, & Neill, 2018). A summary of currently operational plants is provided in Table 21.

Table 21. Operational crop-based biodiesel plants in Canada as of December 2017, shown by location, feedstock and annual capacity in million litres (Biodiesel Magazine, 2019).

Plant Location	Province	Feedstock	Biodiesel Capacity (million L/year)
Lloydminster	AB	Canola	265
Dain City	ON	Canola Oil/Soy Oil	170
Foam Lake	SK	Non-Food Grade Canola Oil	14
Lethbridge	AB	Oilseeds and animal fats	71

Canadian crop-based biodiesel production is dominated by Alberta, which accounted for about 54% of crop-based biodiesel, from canola seed or oil, followed by about 33% from Ontario, based on a mix of canola and soybean, and Alberta, which supplies another 14% from some combination of oilseeds and animal fats (Biodiesel Magazine, 2019).

Canadian biodiesel producers use two primary crops to produce biodiesel: canola and soybean. Table 22 shows the crop volumes produced and used nationally (from (Littlejohns, Rehmann, Murdy, Oo, & Neill, 2018)) along with share of biodiesel production provided by each. Table 23 shows national and regional biodiesel production over 2012-2016 (Natural Resources Canada, 2019).

Table 22: Oilseed crop feedstocks and the share of biodiesel feedstock represented by each for 2016 (Littlejohns, Rehmann, Murdy, Oo, & Neill, 2018)

Crop	Seed area (thousand Ha)	Production (MT)	Biofuel use (MT)	Share of production, Western Canada*	Share of production, Eastern Canada*	Share of national production*
Canola	8236	19600	550	100%	31%	81%
Soybeans	2212	6463	333	3%	33%	10%
Corn oil					37%	9%

* average over 2011-2015, from CEPR data (Natural Resources Canada, 2019)

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[7] The others are based on animal fats and used cooking oils; these processes are covered elsewhere in the document (Section 7).

Table 23: Crop-based biodiesel production in Canada, 2011-2017, in Megaliters (Natural Resources Canada, 2019).

	2011-12	2012-13	2013-14	2014-15	*2015-16*	*2016-17*
Total	121	101	126	124	*18*	*12*
Eastern Biodiesel	111	92	118	110	*2*	*1*
Western Biodiesel	9	8	9	14	*16*	*10*
Share East (%)	92%	92%	93%	88%	*13%*	*12%*
Share West (%)	8%	8%	7%	12%	*87%*	*88%*
Share Canola Oil (%)	83%	100%	93%	91%	*13%*	*12%*
Share Soybean oil (%)	10%	0%	5%	6%	*0%*	*0%*
Share Camelina Oil (%)	0%	0%	0%	0%	*0%*	*0%*
Share other crop (corn oil or canola seed) (%)	7%	0%	1%	4%	*0%*	*0%*

The marked decrease in production volume and feedstock values in Table 23 for 2015-2016 and 2016-2017 reflect a change in number of facilities reporting CEPR data, not a change in actual production.

Conversion to biodiesel

Oilseeds are converted to biodiesel primarily via oil extraction and transesterification. As mentioned, the milling and conversion process(es) yields important co-products – primarily a protein-rich meal and glycerol. The system boundaries and process flow for crop-based biodiesel production from oilseeds are summarized in Figure 5. This includes canola, soybeans, and other oilseeds.

Biodiesel Combustion

Crop-based low carbon liquid fuels are used in overwhelmingly in the transportation sector, either neat (unblended) or blended with their fossil analogues. Biodiesel blends are also sometimes used in generators and boilers. The emissions from combustion of biodiesel depend on efficiency and type of vehicle or engine and the blend level. As it is not feasible to capture the full range of possible combustion scenarios for the vehicle fleet, in the Fuel LCA Modelling Tool the combustion of crop-based biodiesel will be modelled stoichiometrically and harmonized with the Canadian NIR report. A representative vehicle is used here for each fuel (see Section 5.3.5). However, while the bulk of the carbon emissions from combustion of crop-based biodiesel are biogenic and as such are not included in the default carbon intensity for the crop-based biodiesel pathway, the carbon emissions attributable to fossil methanol used in the transesterification process will contribute. These have been be calculated stoichiometrically.

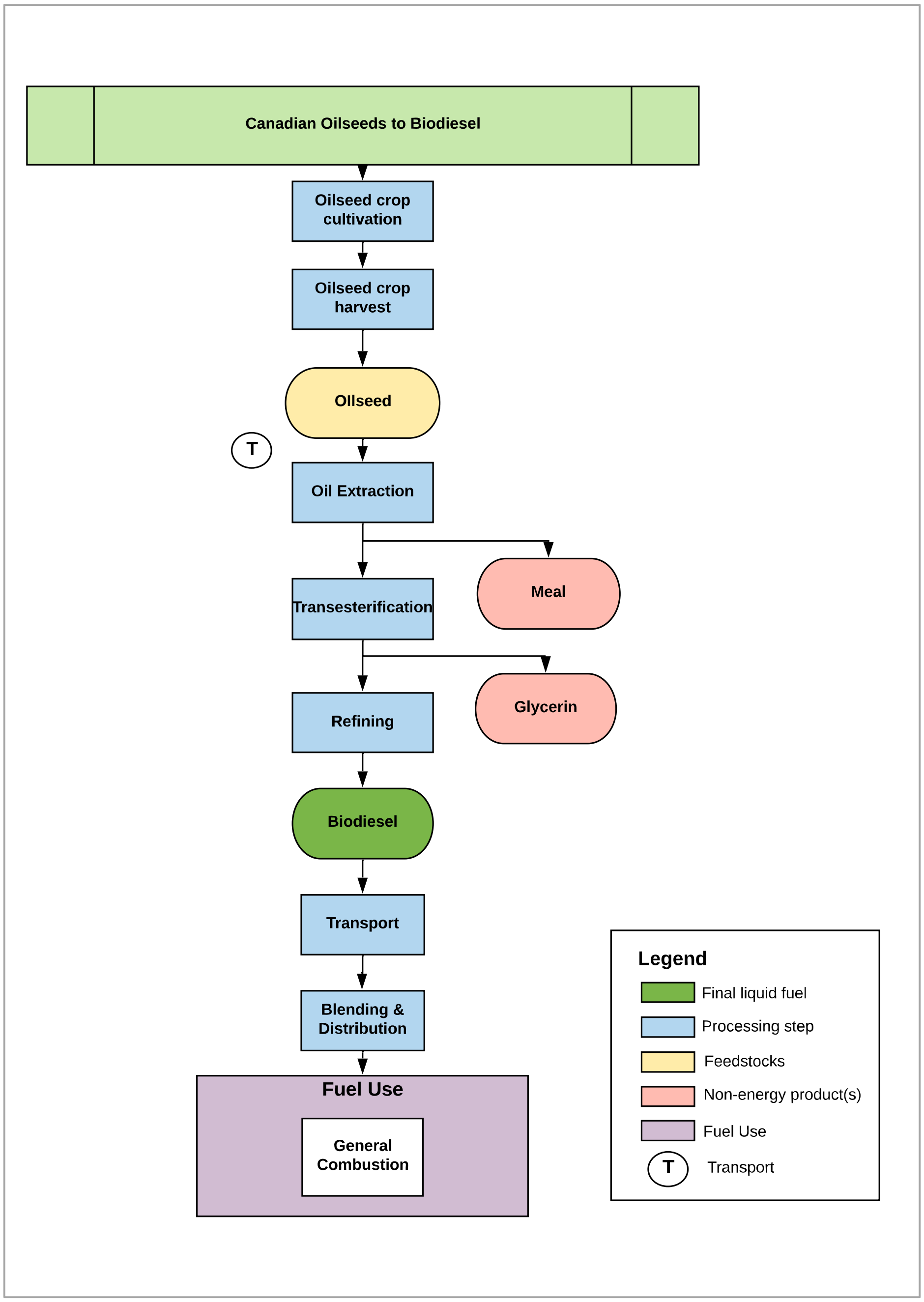

Figure 5. System boundaries and life cycle activities for biodiesel derived from oilseed crop feedstocks, from cultivation to combustion.

5.2 Modelling Approach for Conventional Crop-based Low Carbon Liquid Fuels

5.2.1 Development of Unit Process Building Blocks

The overall modelling approach for Milestone 3 is to develop unit processes to serve as building blocks for current and future modelling work in the Fuel LCA Modelling Tool. In the case of crop-based low carbon liquid fuels this approach is particularly relevant since there are a variety of crop feedstocks that may be used in any fuel conversion process of the matching type (i.e. cereal grains to ethanol via saccharification and fermentation of extracted starch or oilseeds to biodiesel via transesterification of the extracted oil), and these are all based on a basic set of feedstocks that are produced within the Canadian agricultural industry, and a set of conversion processes associated with the conversion type.

The key building blocks for crop-based low carbon liquid fuels are summarized from a modeling perspective in Figure 6. They include feedstock crop production activities; transportation to processing; conversion to starch- or oil-based fuel; transportation, blending and/or storage, and distribution; and combustion. With these building blocks in place, reflecting regional variation where possible (*e.g.,* differences in crop yields, agrichemical inputs, fuel consumption, differences in electricity grids, *etc*.), users of the Fuel LCA Modelling Tool who want to build a crop-based biofuel process can select the appropriate feedstock(s) from the available building blocks and pull them in to their specific fuel production pathway. They can also copy and modify these building blocks with their own more recent or process-specific data.

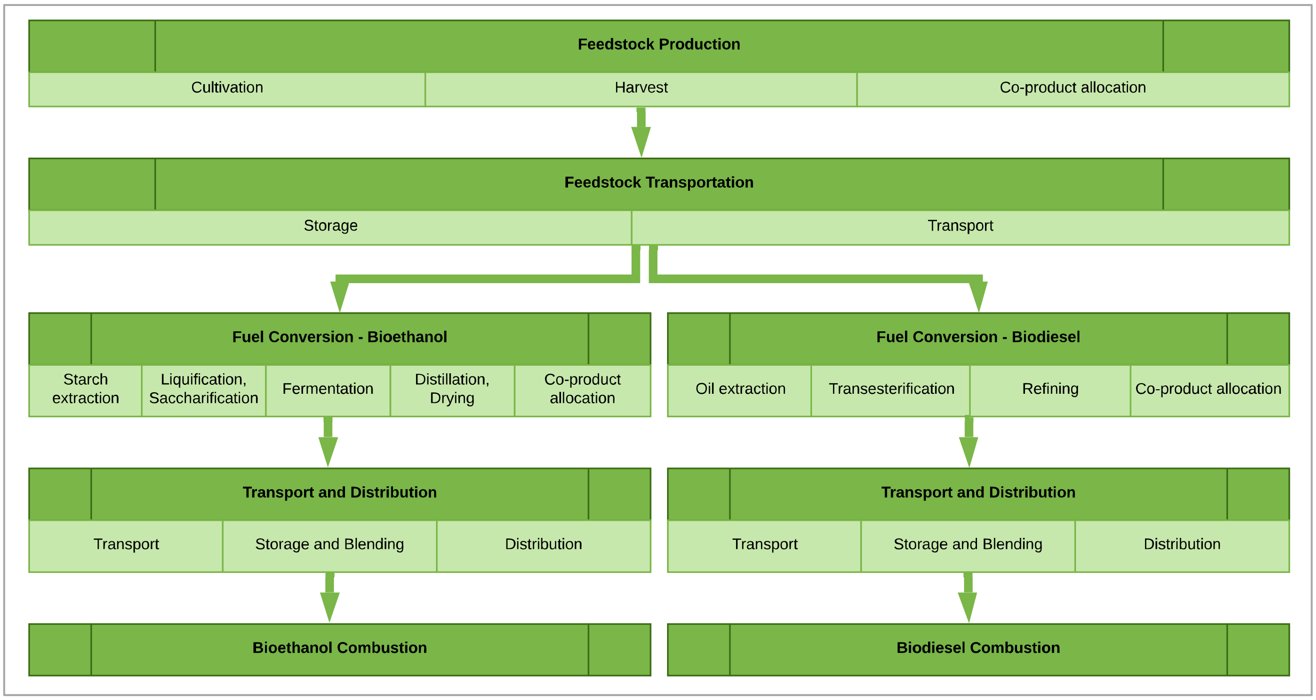

Figure 6: Building blocks of the crop-based conventional biofuels pathways

5.2.2 Regional Variation

The primary regional variations for crop-based low carbon liquid fuels arise from the production of the feedstock more than the conversion technology. These will influence carbon intensity, as they reflect differences in crop management practices reflecting to the local microclimate. These include crop yield, agrochemical use, water use, and some harvest practices, including highly localized variation in harvest residue collection. The latter variation affects the crop residue-derived lignocellulosic fuels. Other regional variation can arise from background energy systems such as variations in electricity grids providing energy to fuel conversion processes. The sourcing of regional/provincial feedstocks could also influence transport distances and modes for feedstock delivery and final fuel delivery.

These differences are reflected in the modelling as much as possible within the confines of the available data. For example, crop management and harvesting data is available at a provincial level but may vary for an individual producer. Thus, tool users will need to choose a unit process from the most appropriate region or choose the unit process for Canadian average management and harvesting or would need to model more specific harvesting data in this version of the Fuel LCA Modelling Tool. In such cases, the tool user could then modify a copy of an existing unit process or build their own from scratch to reflect their case based on the data they have available[8].

With respect to background energy systems, electricity grid carbon intensities are available at a provincial level based on work completed in Milestone 2, as are some fuels (e.g., diesel), and have been incorporated into the unit processes available for modelling crop-based low carbon liquid fuels. For example, modelling the production of corn bioethanol in Ontario could include the use of Ontario electricity to power the grain handling and conversion process.

5.2.3 Co-Product Allocation

The need to address co-product allocation is a prominent issue for crop-based low carbon liquid fuels as all conventional fuel processes produce multiple saleable products. In addition, agricultural residues from both grain and oilseed crops used for conventional biofuels may be a co-product of the crop production system, or may be considered a waste. Both the conversion of grain crops and oilseeds to fuels provide substantial co-products from primary processes including livestock feeds and other goods. The upstream carbon intensity from their production as part of the fuel production process must be allocated between the primary product and the co-products. In the future as unconventional fuels gain market share, agricultural residues, such as corn stover from corn cultivation, will need to be considered as co-products from primary processes and the upstream carbon intensity from their production will have to be allocated between the primary product and the co-products, influencing the carbon intensity of both the primary crop and the utilized residue.

As discussed above (Section 2.8), the choice of allocation approach must be well-documented and transparent, including a clear rationale and sensitivity analysis to show the influence on the study results. Different allocation decisions significantly affect final results (Wang, Huo, & Arora, 2011), and has demonstrated to influence the ability of a fuel to meet a greenhouse gas reduction target (Kaufman, Meier, Sinistore, & Reinemann, 2010).

In Milestone 1 and 2 it was established through discussions with ECCC that upstream carbon intensity would be allocated to co-products according to energy content. Milestone 3 has continued this process. More generally, using the building blocks approach for the Fuel LCA Modelling Tool, the capability to choose different allocation approaches will be incorporated in the tool. For example, allocation of upstream impacts to extracted oil and protein co-products from oil seeds is often done by mass in the literature and other established tools (Wang, Huo, & Arora, 2011), and may be

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[8] In the same way, higher resolution processes, such as at the reconciliation unit level, can readily be added by users and administrators, simply by editing a copy of an existing provincial process and updating values to those they have collected in their research or reporting.

determined to be a more appropriate way of allocating for crop-based low carbon fuel feedstocks. Either allocation by mass or energy are\ consistent with the ISO 14044 guidelines since both ways of allocating are based on a physical relationship between the inputs and outputs of the system. In other instances, there may be good rationale to use displacement instead of allocating.

5.2.4 Biogenic Carbon and Land Use Change

In remaining consistent with the Government of Canada's policy on biogenic carbon, as shown in Canada's National Inventory Report (Government of Canada, 2018), emissions of biogenic carbon from combustion of crop-based low carbon liquid fuels is not included in the carbon intensity calculations. Biogenic carbon emissions will be calculated and reported separately from the default carbon intensity values.

Carbon emissions associated with direct land use change will be included in instances where feedstock production requires the conversion of land from existing use to bioenergy production. In the case of crop-based low carbon fuels, this would arise with the conversion of new agricultural land, and, potentially, with use of previously fallow land. The method for including direct land use change will require further and ongoing discussion with ECCC. The results of the uncertainty analysis on Canadian average production for these crops are shown in Table 35.

Data quality and uncertainty in crop production, land occupation and transformation is both a significant contributor and highly uncertain. Indirect land use change is excluded from the carbon intensity calculations.

5.3 Life Cycle Inventory for Conventional Crop-based Low Carbon Liquid Fuels

5.3.1 Feedstock Production – Agricultural Cropping Systems

Feedstock production for crops included in the crop-based low carbon liquid fuels were modelled using the GHG emissions from Canadian cultivation. This is described in Section 4. Agricultural Systems for Crop-Based Low Carbon Liquid Fuels. Relevant crops covered in the CALCD agricultural LCI are summarized in Table 24. The CI values for these crops can be found in Table 9 and Table 10, in Section 4.7.

Table 24. Crops included or to be included (italics) in the CALDC agricultural LCI library.

Grains	Oilseeds
Corn	Canola
Wheat	Soybean
Barley	Camelina

5.3.2 Storage and transport

Transport of harvest grain and oilseed from the field to the silo and storage sites is included in the CALCD library. Transport of the grain or oilseed to distilleries and mills is modeled by estimating average transport distance based on crop production locations and using unit processes for truck and rail transport developed in Milestone 2. The values used are shown in Table 25. Further details are provided in Appendix B.

Table 25. Transportation modes and distances for crop-based conventional biofuel feedstocks.

Life Cycle Stage	Biofuel/Feedstock	Average Distance	Primary Mode
Feedstock Transport	Agricultural feedstocks (grain, seed)	100 km	Truck

5.3.3 Fuel Production

Detailed provincial and anonymized LCI data for Canadian grain bioethanol and Canadian oilseed biodiesel has been compiled by NRCan as part of the NRCan's ecoENERGY for Biofuels Program, which ran between 2008 and 2017 (Natural Resources Canada, 2019). The data is aggregated from information provided in Complementary Environmental Performance Reports (CEPR). The data tables are attached as Appendix D (bioethanol) and Appendix E (biodiesel). For these models, the CEPR data has been corrected for unit inconsistencies in reporting of material inputs where necessary[9]. The CEPR data has been used to develop Canadian average bioethanol and biodiesel pathways. In addition, pathway templates have been developed for common routes.

Inputs below a (mass) cutoff of 0.1% are excluded, except for enzymes and yeast. Analysis of the CEPR data shows no systemic shifts over the 2009/10-2015 period, so the reported data are averaged over the period (omitting mid-2015 on as producer response rates decline dramatically with production incentives) and the facilities to develop the processing portion of the pathway. Some bioethanol facilities make excess electricity, but the net electricity purchased from grid is always positive. For transparency, if an electricity coproduct is exported to grid, it is included as a negative flow (i.e., used to displace an equivalent amount of the grid electricity purchased).

Table 26. Mass balance and material and energy inputs for production of bioethanol from grains for Canadian facilities, from averaged (2012-2016) producer data (CEPR).

Bioethanol Production	Canadian Average	Dry Mills	Wet Mills	Dry Mill Corn	Wet Mill Wheat
Starch Sources	Mixed Grains (wheat, corn, barley)	Mixed Grains (wheat, corn, barley)	Mixed Grains (wheat, corn, barley)	Corn	Wheat
Dominant Region	West/Alberta, Manitoba, Saskatchewan	West/Alberta, Manitoba, Saskatchewan	West/Alberta, Manitoba, Saskatchewan	West/Ontario	West/Saskatchewan
Feedstock					
Corn (kg)	0.0823	0.0925	0.0055	0.1026	-
Wheat (kg)	0.0218	0.0116	0.0987	-	0.1139
Barley (kg)	0.0008	-	0.0067	-	-
Material & Energy Inputs					
Natural Gas (MJ)	0.4039	0.3683	0.6716	0.3590	0.6967
Electricity from Grid (kWh)	0.00931	0.00870	0.0139	0.0074	0.0193
LFO (MJ)	0.00058	0.00065	-	0.00081	-
HFO (bunker c) (MJ)	0.00161	0.00183	-	0.00226	-

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[9] In several cases a producer's reported value for an input for a year was given in kilograms rather than tonnes, as evidenced by a deviation of approximately three orders of magnitude from other values.

alpha-amylase (kg)	0.00051	2.81E-05	0.00048	2.42E-05	0.00069
glucoamylase (kg)	0.00119	5.27E-05	0.00078	5.28E-05	0.00085
Yeast (kg)	5.90E-06	4.13E-06	1.94E-05	3.89E-06	1.24E-05
Ammonia (kg)	8.43E-05	9.55E-05	-	0.00012	-
Caustic soda (kg)	0.00025	0.00022	0.00046	0.00016	0.00038
Urea (kg)	0.00021	0.00021	0.00016	0.00019	0.00020
Sulphuric acid (kg)	0.07556	0.08485	0.00639	0.10011	0.02923
Uncaptured fermentation CO2 emissions (kg)	0.0134	0.0151	-	0.01304	-
Captured fermentation CO2 emissions (kg)	0.0043	0.0048	-	0.00443	-
*Outputs***					
Bioethanol (MJ)	1	1	1	1	1
Electricity to grid (kWh)	-3.45E-05	-3.89E-05	-	-4.85E-05	-
Combined feed, dry basis (MJ)	0.667	0.640	0.868	0.636	0.560
DDG (MJ)	0.1018	0.1018	0.1018	0.0403	-
WDG (MJ)	0.1087	0.1087	0.1087	0.0577	-
DDGS (MJ)	0.3328	0.3328	0.3328	0.3440	0.7307
WDGS (MJ)	0.2297	0.2297	0.2297	0.5120	-
Corn oil (MJ)	0.0050	0.0056	-	0.0070	-

**The pathway is for undenatured fuel ethanol, so gasoline is not included in the inventory. **Note – Where coproduct values were not provided in MJ, the energy contents used are from* (Heuzé V., 2017; DM INRA-CIRAD-AFZ , n.d.). *A summary table is in Appendix A2, Table 114.*

Table 27. Mass balance and material and energy inputs for extraction of bio oils from oilseeds in an average Canadian facility from literature (Chen, et al., 2018) (Shonnard, Williams, & Kalnes) (Miller & Kumar, 2013) (Li & Mupondwa, 2014)

Biodiesel Production	**Soybean oil Amount (per kg of oil)**	**Canola oil Amount (per kg of oil)**	**Camelina oil Amount (per kg of oil**
Inputs			
Oil seed (kg dry matter)	4.6	2.2	2.9
Natural gas (MJ)	4.1	2.43	1.812
Electricity (kWh)	0.194	0.114	0.0304
Light Fuel Oil (MJ)	0.03	0	0
Heavy Fuel Oil (MJ)	0	0	0
Hexane (kg)	0.0012	0.023	0.024
Outputs			
Biooil	1	1	1
Meal/Cake, dry mass	3.5	1.11	1.71
*Output energy contents (HHV)**			
Biooil, MJ/kg	39.3	39.3	1
Meal/Cake, MJ/kg	19.7	19.4	22.1

***Note – Biooils and coproduct values when not provided in MJ use energy contents from* (Heuzé V., 2017; DM INRA-CIRAD-AFZ , n.d.). *A summary table is in Appendix A2, Table 114.*

Table 28. Mass balance and material and energy inputs for production of biodiesel form bio oils in an average Canadian facility from producer data (CEPR) and literature (Chen, et al., 2018).

Biodiesel Production	Producer Data (per MJ of biodiesel)	Generic (literature) Vegetable Oil (per MJ of biodiesel)
Inputs		
Oilseed oil	0.272	0.0248
Natural gas (MJ)	0.0912	0.0294
Electricity (kWh)	0.00306	0.00102
Biodiesel distillation bottoms (MJ)	0.0262	1.24E-05
Light Fuel Oil (MJ)	0.000346	
Recycled grease (MJ)	0.00108	
Methanol (kg)	0.00272	0.00269
Sulfuric acid (kg)	0.000326	2.49E-06
Hydrochloric acid (kg)	0	6.22E-05
Sodium methylate (kg)	0.000378	0.000122
Sodium hydroxide (kg)	1.21E-05	9.96E-06
Potassium hydroxide (kg)	0.000441	0
Nitrogen gas (kg)	0	5.47E-05
Phosphoric acid (kg)	0	9.96E-06
Outputs		
Glycerol (kg)	0.0042	0.00226
Biodiesel distillation bottoms (kg)	0.00096	7.47E-05
Fatty acids (kg)	0	0.000107

**Note – The energy contents of the co-products include (Chen et al. 2018): glycerol - 18.56 MJ/kg; biodiesel distillation bottoms – 39.47 MJ/kg; fatty acids – 39.47 MJ/kg. The energy content of biodiesel is 29.67 MJ/kg.*

In the Fuel LCA Modelling Tool, uncertainty analysis will be used to capture the influence of the range in energy and materials consumption evident in the compiled Complementary Environmental Performance Reports on the default carbon intensity.

The facility level and aggregate data provided for Canadian bioethanol producers (Natural Resources Canada, 2019) do not distinguish between wet and dry milling. However, the inputs and co-products in the unit process accessible in the Fuel LCA Modelling tool will readily adaptable by the user to accommodate either (or other variations).

The carbon intensity for electricity, fuels and natural gas was obtained from the results of the Milestone 2 work on carbon intensity of Canadian fossil fuels (EarthShift Global, WSP, Introspective Systems, 2019). The default carbon intensity of crop-based bioethanol and biodiesel was modeled using a Canadian average electricity grid; however, users of the Fuel LCA Modelling tool will be able to incorporate regional electricity and fuel sources to calculate the carbon intensity for production in different provinces.

These values reflect the types of variation that may be observed in fuel production LCI data. This variation is captured in the uncertainty analysis but may also be addressed by the addition of more specific data from low carbon fuel producers using the Fuel LCA Modelling Tool.

5.3.4 Fuel Transport

Moisture content, and its associated effect on density, is important consideration for feedstock transport. As such, the feedstock transport must account for the density variation between crop-based feedstocks, whether grain or oilseed.

The transportation of both feedstocks and final liquid fuels are primarily via truck and rail. In modelling this transport, we use the truck and train unit processes that were created in Milestone 2 (EarthShift Global, WSP, Introspective Systems, 2019) to capture the upstream and combustion emissions associated with these modes of transport.

Transportation modes and distances are addressed **in Appendix B**. Table 29 summarizes the relevant transportation modes and distances used in this analysis. While both ethanol and biodiesel are also transported by rail, with about 70% of North American ethanol transported by rail to market (RFA, 2017), only 5-10% of Canadian fuel products were distributed via rail from primary terminal in 2016 (Kent Group, 2017).

Table 29. Transportation modes and distances for crop-based biofuel fuels.

Life Cycle Stage	Biofuel/Feedstock	Average Distance	Primary Mode
Fuel Transport	Biofuels (liquids)	600 km	Rail
Fuel Distribution	Biofuels (liquids)	290 km	Truck

5.3.5 Combustion

Fuel characteristics and emissions factors for combustion of crop-based conventional biofuels are summarized in Table 30.

Table 30. Characteristics and combustion emissions of ethanol and biodiesel (Government of Canada, 2018).

Fuel	Application	Density	High Heating Value	Carbon Content	CO_2 (g/L fuel)	Carbon source	Fossil CO_2 (g/L fuel)
Ethanol	Transportation	789.3kg/m^3	29.67 kJ/g	52.14%	1,508	biogenic	0
Biodiesel	Primarily Transportation	882kg/m^3	39.89 kJ/g	75.6%	2,472*	biogenic & fossil	139.6**

** fossil diesel emissions used in NIR.*

*** from fossil methanol used in production. This value has some additional variability because it is tied to the methanol mass balance in the transesterification process and is calculated as part of the pathway.*

Table 31. Representative transport combustion emissions of ethanol and biodiesel, from Table A6-12 (Government of Canada, 2018).

Fuel	Mode	CO_2 g/L fuel	CH_4 g/L fuel	N_2O g/L fuel
Ethanol	Light-duty Gasoline Vehicles (LDGV), Tier 2	2,307	0.014*	0.022*
Biodiesel	Heavy-duty Diesel Vehicles (HDDV), Moderate Control	2,472	0.014**	0.082**

** fossil gasoline emissions used in NIR; ** fossil diesel emissions used in NIR.*

Fuel Combustion – Bioethanol

Bioethanol is primarily for transportation. At present, it considered for use in transportation blended with conventional gasoline.

The CO_2 emissions from combustion of crop-based bioethanol are biogenic since they are from agricultural feedstocks. As such, although these emissions are included in the tool and reported separately in the data sheets; they are not included in the default carbon intensity values for crop-based low carbon liquid fuels. Tool users will be able to include or exclude biogenic carbon in their analyses.

Fuel Combustion – Biodiesel

Biodiesel can be used in various energy applications, primarily transportation but also including combustion in industrial or residential boilers and generators. At present, biodiesel is most often considered for use in transportation when blended with conventional diesel.

Most of the CO_2 emissions from biodiesel combustion are biogenic since they are from agricultural feedstocks. As such, although these emissions are included in the tool and reported separately in the data sheets; they are not included in the default carbon intensity values for low carbon solid fuels. However, the methanol used in transesterification maybe from fossil or bio-based.

The Canadian National Inventory Report does not provide specific emission factors for CH_4 and N_2O for biodiesel (Government of Canada, 2018), instead utilizing emissions factors for the combustion of fossil fuel-based diesel. To augment this, literature values for biodiesel combustion and the non-biogenic emissions attributable to the use of fossil-fuel-derived methanol have been incorporated.

For the default crop-based biodiesel pathways in the Fuel LCA Modelling Tool, the modelled end use will be direct combustion. Emissions factors for this combustion will be derived from literature sources. The direct combustion emissions can be scaled by the user for efficiency and other characteristics of the engine (stationary or mobile) in which it is used.

5.3.6 Modelling and Life Cycle Inventory for bioethanol from dried peas

A carbon intensity value for conventional bioethanol from dried peas has been developed to support a template pathway in the final tool. As a highly speculative pathway, it requires more approximations than other pathways, and the increase in uncertainty should be kept in mind. The approach described here is a useful screening approach.

Feedstock Production and Transport

The Canadian Roundtable on Sustainable Crops (CRSC) life cycle analysis did not include LCI data for pea cultivation in Canada, and as such, this feedstock is not included in the CALCD dataset. The CI for pea production in Canada, 0.38 kg CO_2 eq./kg dry matter, was obtained from table 18-2 in Desjardins et al (2016). Transport distances for feedstock delivery were assumed to be the same as for corn or wheat.

Processing of Feedstock into Fuel

Process data is not available for bioethanol using dried peas as a feedstock, and there are currently no commercial processes using it in Canada. There is one report of starch extracted from peas being added to mixed grain processing, but anecdotal data indicates that dried pea starch is sometimes added with other grain feedstocks in more common practice.

The key parameters needed are 1) ethanol yield per kilogram of grain/legume; 2) co-product type, amount and energy density; and 3) change in energy and input needs from the base grains that have been modelled for other pathways.

In cases where process data is not available, the bioethanol from grain fermentation process developed from producer-reported data has been used as a base case and scaled using the differences in ethanol yield between the grain of interest and corn. Because ethanol is produced from the starch portion of the grain, the starch content can be used as a proxy for ethanol yield to allow for scaling of the process emissions. This is equivalent to scaling each of the inputs relative to the ratio of feedstock starch content to corn and assuming that there are not other factors specific to the feedstock.

To develop the value for a pea-based bioethanol CI, the starch content (51.5%, or 69.9% that of corn, on a dry matter basis (Heuzé V., 2017) (DM INRA-CIRAD-AFZ , n.d.) has been used to estimate the ethanol yield from pea relative to that from corn. In the absence of data specific to the pea process or legumes/pulses generally, the unallocated life cycle processing emissions are scaled by the difference in yield. As corn and wheat process emissions differ and peas are legumes rather than cereal grains, the mixed grains (corn, wheat, barley) producer process is used here, and the corn and wheat process emissions (scaled) are used to set a range for uncertainty analysis.

Like the grains currently used for conventional bioethanol production, the legume pea also produces nutrient rich residue, pea protein concentrate. To estimate co-product yields, the protein in the legume is assumed to be entirely converted into the pea protein concentrate. The literature value of 22.8MJ/kg was used for the protein content of peas (Heuzé V., 2017) and the energy content of pea protein concentrate (DM INRA-CIRAD-AFZ , n.d.).The process and upstream emissions are allocated between the bioethanol product and pea protein co-product on an energy basis (45% to pea protein coproduct, in line with corn's 49% allocation and wheat's 42%).

5.4 Carbon Intensity Results for Conventional Crop-Based Low Carbon Liquid Fuels

5.4.1 Carbon Intensities for Crop-based Bioethanol

Table 32 shows the CI values for a variety of pathways and templates. These are intended to provide an easy starting point for modelling many province-specific processes and feedstocks. The top set of pathways uses producer data reported under the ecoEBE program for the grain to bioethanol block, while the lower set of template pathways use literature data.

Table 32. Provincial and Canadian average cradle-to-grave carbon intensity values for key crop-based conventional biofuels, expressed in g CO_2 eq./MJ of fuel.

Crop-based fuel pathway	Carbon Intensity (g CO_2 eq./MJ)
Bioethanol	
Bioethanol – Producer Sourcing and Operating Data	
Canadian Average Bioethanol from Mixed Grains, Producer Sourcing & Processing Data	45
Dry milling from Mixed Grains, Canadian Average, Producer Sourcing & Processing Data	41
Wet milling from Mixed Grains, Canadian Average, Producer Sourcing & Processing Data	40
Dry milling from Corn, Canadian Average, Producer Sourcing & Processing Data	42
Wet milling from Wheat, Canadian Average, Producer Sourcing & Processing Data	51
Bioethanol – Approximated with Producer Sourcing and Operating Data	
Canadian Average Bioethanol from Dry Peas, Estimated* Sourcing & Processing	55
Canadian Average Bioethanol from Barley, Average Sourcing & Estimated* Processing	35

Of the 14 facilities, ten are dry mill (seven are corn exclusively) and four wet mill. Only two facilities are using exclusively wheat, and are wet milling. The CI for bioethanol from wheat via wet milling is correspondingly less robust. In addition to the producer-reported data pathways, the dried pea and barley pathway CIs are included with a pathway based on scaled inventories from the producer data. For both, the pathway and CI should be taken as a starting point for development of a more detailed representative pathway. The CALDC does not yet contain an inventory for dried peas, so the dried pea ethanol CI appears higher than the others but is likely to decrease when the CRSC-based dried pea is added.

Table 33 shows the carbon intensity values for bioethanol production based on current operations and the CEPR reporting data, total and broken down by life cycle stage for different levels of technology and feedstock aggregations.

Table 33: Carbon intensity values for currently produced grain-based bioethanol (producer data 2012-2016), per MJ of fuel produced, allocated with harvesting coproducts by mass and processing coproducts by energy share, to two significant figures.

Life Cycle Stage	Canadian Average	Dry Mills	Wet Mills	Dry Mill Corn	Wet Mill Wheat
Life Cycle Stage	Mixed Grains (wheat, corn, barley)	Mixed Grains (wheat, corn, barley)	Mixed Grains (wheat, corn, barley)	Corn	Wheat
Feedstock Production	20	21	11	22	13
Feedstock Transportation	0.9	0.9	0.9	0.9	1.1
Process emissions	23	18	27	18	35
Transport & Distribution	0.8	0.8	0.8	0.8	0.8
Combustion	0.4	0.4	0.4	0.4	0.4
Total	45	41	40	42	51

Table 34 total and building block contributions to the CI for bioethanol from dried peas and bioethanol made entirely from barley (as opposed to the Mixed Grains process in the CEPR data), neither of which had data in the CEPR materials. Both use a yield-scaled mixed grains bioethanol average process from CEPR data.

The CI to make bioethanol from dried peas with a protein-rich coproduct is allocated (energy basis) to give the values here. The bioethanol from barley CI is also allocated (energy basis) between the bioethanol and coproduct. The primary contributors to the life cycle GHG emissions are the feedstock production and emissions associated with energy use and chemical inputs for conversion to ethanol.

Table 34. Carbon intensity for ethanol produced from pea starch and barley based on scaling the CEPR process, expressed in g CO_2 eq. per MJ of ethanol.

Life Cycle Stage	Dried Peas (g CO2eq/MJ)	100% Barley (g CO2eq/MJ)	Unit
Feedstock Production	29	10	g CO_2 eq./MJ
Feedstock Transport	1.3	1.1	g CO_2 eq./MJ
Ethanol Production	23	22	g CO_2 eq./MJ
Transport & Distribution	0.8	0.8	g CO_2 eq./MJ
Combustion	0.4	0.4	g CO_2 eq./MJ
Total	55	32	g CO_2 eq./MJ

The significantly lower fraction of starch in dried peas compared to the other grains, including barley, results in a much higher feedstock demand and consequently a significantly higher CI value for Bioethanol from (100%) Dried Peas. In contrast, the CI and contributions for Bioethanol from 100% Barley is in the same range as the other CIs.

Results of the uncertainty analysis on the bioethanol pathways are shown in Table 39. The CI values for all pathways show broad uncertainty ranges, dominated by uncertainty in the crop production CI. The range on the wet mill mixed grain CI is larger because of the higher variability in that data and the smaller number of facilities.

Table 35. Results of uncertainty analyses for crop-based bioethanol based on producer data, g CO_2 eq/MJ ethanol. Results based on Monte Carlo analysis of 2,000 runs with a confidence interval of 95%.

Final CI	Mean	Median	SD	Min (2.5%)	Max (97.5%)
Bioethanol – – Producer Sourcing and Operating Data					
Canadian Average Bioethanol from Mixed Grains, Producer Sourcing & Processing Data {CA}					
45	52.9	51	12	36.1	80.2
Dry milling from Mixed Grains, Canadian Average, Producer Sourcing & Processing Data {CA}					
41	47.1	45.4	11	31.1	73.1
Wet milling from Mixed Grains, Canadian Average, Producer Sourcing & Processing Data {CA}					
40	62.2	59.7	16	38.7	102
Dry milling from Corn, Canadian Average, Producer Sourcing & Processing Data {CA}					
42	45.8	44.1	10	30.5	70.5
Wet milling from Wheat, Canadian Average, Producer Sourcing & Processing Data {CA}					
51	78.1	74.7	20	47	128
Bioethanol – Approximated with Producer Sourcing and Operating Data					
Canadian dry mill bioethanol from Canadian Dried Peas {CA}					
55	79.8	56.6	85	29	269
Canadian dry mill bioethanol from Canadian Barley {CA}					
35	87.8	67.7	70	31	269

The uncertainties for the CI values for all pathways are high primarily due to uncertainty in the agricultural production (i.e., what the intensity associated with any particular kg of grain in Canada, which could range from the minimum fount nationally to the maximum found national), and, in the case of dried peas and 100% barley, lack of dedicated process data. In fact, the agricultural uncertainty overwhelms uncertainties in the other life cycle stages with the exception of bioethanol from dried peas, which is a more speculative pathway based on approximations to the CEPR process. The dried peas, higher protein pulses, deviate more from the underlying process than does the grain barley. The Barley conversion process is much better represented by the CEPR data, as it is a feedstock in mixed production, and because its composition has more in common with the other grains, but barley production impacts are variable.

5.4.2 Carbon Intensities for Crop-based Biodiesel

The pathway carbon intensity values, from crop production though to combustion at the user, for oilseed crop-based biodiesel are shown in Table 36. The two sets of pathways use producer data reported under the ecoEBE program for the oil to biodiesel block and oilseed-specific literature data for the oil extraction block (top) or literature values for both blocks (bottom). The CI values from each are nearly identical.

Table 36. Provincial and Canadian average cradle-to-grave carbon intensity values for included crop-based biodiesel pathways, expressed in g CO_2 eq./MJ of fuel.

Crop-based fuel pathway	Carbon Intensity (g CO_2 eq./MJ)
Biodiesel – Producer Operating Data for Oil to Biodiesel	
Canadian Average Biodiesel from Canola, Producer Processing Data	31
Canadian Average Biodiesel from Soybean, Producer Processing Data	36
Canadian Average Biodiesel from Camelina, Producer Processing Data	22
Biodiesel – Generic Vegetable Oil to Biodiesel Template Pathways	
Canadian Biodiesel from Canadian Canola	24
Canadian Biodiesel from Canadian Soybean	29
Canadian Biodiesel from Canadian Camelina	16

As described in Section 3, a building block approach has been used to develop CI values for conventional crop-based biofuels to provide CI values and easily modifiable templates in the Tool to facilitate modeling. Oilseed-based building block and cumulative biodiesel CI values are shown in Table 37 and Table 38. Table 37 uses producer data reported under the ecoEBE program for the oil to biodiesel block, while the values in Table 38 are based on literature data for general vegetable oil to biodiesel conversion. In both cases, oil extraction is represented by building blocks for each of the feedstocks developed from literature.

Table 37: Building block and cumulative carbon intensity values for oilseed-based biodiesel based on oilseed specific extraction and current (2012-2016) biodiesel production (producer data) for biodiesel conversion, per MJ of fuel produced, impacts allocated with coproducts by energy share.

Life Cycle Stage	Canola	Soy	Camelina	Unit
Feedstock Production	13	17	5.1	g CO_2e/MJ
Feedstock Transportation	0.5	0.6	0.5	g CO_2e/MJ
Oil extraction @ Mill/Refinery	2.7	4.2	1.6	g CO_2e/MJ
Oil to Biodiesel Conversion @ Mill/Refinery	9.8	9.8	9.8	g CO_2e/MJ
Transport & Distribution	*0.6*	*0.6*	*0.6*	g CO2e/MJ
Combustion (non-biogenic)	4.4	4.4	4.4	g CO_2e/MJ
Total	31	36	22	g CO_2e/MJ

Table 38 Building block and cumulative carbon intensity values for oilseed-based biodiesel based on oilseed specific extraction and literature data for biodiesel conversion per MJ of fuel produced, impacts allocated with coproducts by energy.

Life Cycle Stage	Canola	Soy	Camelina	Unit
Feedstock Production	13	16	4.9	g CO_2e/MJ
Feedstock Transportation	0.5	0.6	0.5	g CO_2e/MJ
Oil extraction @ Mill/Refinery	2.6	4.0	1.6	g CO_2e/MJ
Oil to Biodiesel Conversion @ Mill/Refinery	3.5	3.5	3.5	g CO_2e/MJ
Transport & Distribution	0.6	0.6	0.6	g CO2e/MJ
Combustion (non-biogenic)	4.5	4.5	4.5	g CO_2e/MJ
Total	24	29	16	g CO_2e/MJ

The producer-specific reported data which underpins the production CIs in Table 38 are in very good agreement with the literature-based processes in Table 37. The only significant difference between the two arises from a much higher reported natural gas usage in the producer (CEPR) data, which differs by a factor of 3, and leading to the higher CI for oil to biodiesel and total CI seen in the industry pathway.

Results of the uncertainty analysis on the biodiesel pathways are shown in Table 39. The deviation between the single point CI and the mean values arises from the large, highly variable ranges for the feedstock production (agriculture) stage, which is attributable to the SOC range and impact.

Table 39. Results of uncertainty analyses for crop-based biodiesels. Results based on Monte Carlo analysis of 2,000 runs with a confidence interval of 95%.

Final CI	Mean	Median	SD	Min (2.5%)	Max (97.5%)
Literature-based oil extraction and Producer data (CEPR) conversion to biodiesel					
Canadian biodiesel from Canadian canola seeds {CA}					
31	44.8	30.5	45.6	14.2	171
Canadian biodiesel from Canadian soybeans {CA}					
36	62.4	40.9	65.9	17.7	228
Canadian biodiesel from Canadian camelina seeds {CA}					
22	23.9	20.9	36	-2.9	93.1
Literature-based oil extraction and conversion to biodiesel					
Canadian biodiesel from Canadian canola seeds {CA}					
24	45.3	30.4	54.8	14.4	169
Canadian biodiesel from Canadian soybeans {CA}					
29	67.2	39.4	100	17.5	279
Canadian biodiesel from Canadian camelina seeds {CA}					
16	17.8	14	29	-2.4	79.6

The CI values for all pathways show high levels of uncertainty, primarily arising from uncertainty in the crop production CI. This large uncertainty overwhelms uncertainties in the other life cycle stages. This is particularly apparent in the CI for camelina-based fuels. As a currently very low production crop, agricultural practice data is highly uncertain, resulting in the high ranges for camelina; the negative minimum values reflect the range in soil organic carbon emissions associated with management practice change and may suggest potential for some carbon sequestration with camelina.

Oilseeds represent a small share of current Canadian biodiesel production. The oil to biodiesel process built from the operating data contained in the CEPR thus doesn't align as well with oilseed practices. In these cases, the generic, literature-based pathway may represent a better starting point.

5.5 Data Gaps and Limitations for Conventional Crop-Based Low Carbon Liquid Fuels

Data gaps relevant for the crop-based low carbon liquid fuels include:

- Cultivation
  - Detailed land management information (e.g. extent of till/no till) and spatially-explicit monitoring of
    - Consolidation and storage variability
    - Distance and mode variation
- Production
  - Consistent co-product energy (and other input) use data, which would facilitate alternative allocation approaches
  - The CEPR data indicate that there was only a single facility from which surplus electricity was exported from crop-based bioethanol producers during the reporting period (data spans 2008/09 to 2016/17, with good coverage 2010/11-2015). This case is reflected in the corn pathway, but anecdotal reports suggest electricity export is more frequent.
  - Because oilseeds represent a small share of current Canadian biodiesel production compare to other oils, the operating data contained in the CEPR may not align well with oilseed practices. As the CEPR data is no longer updated and

    is used to create a snapshot process, data from other producer reporting schemes may fill this gap. Literature-based processes have been built as templates to use with vegetable and other oils for biodiesel.
  - Ongoing and updated operating data associated with a selection of technology types would allow for defensible association of technology pathway in cases where there are multiple and substantively differing technology routes. For example, the conventional bioethanol process based on CEPR data is a hybrid of technology and feedstock.
- Dried Peas and other feedstocks not captured in the producer data
  - Feedstock-specific differences in processing energy and input demands. Process emissions differ significantly even between wheat and corn, which are more similar to each other than to peas (and other legumes/pulses), which have a much higher protein content (2-2.5x). While scaling the process emissions relative to yield is a reasonable first-order approximation, the difference between crop families increases the uncertainty significantly.
  - Detailed agricultural practice data for cultivation, harvest and storage of peas in Canada.

6. Unconventional Crop-Based Low Carbon Liquid Fuels

6.1 Introduction to Unconventional Crop-based Low Carbon Liquid Fuels

As discussed in Section 5, low carbon liquid fuels can be produced from a variety of renewable Canadian crops, whether grains (e.g., conventional bioethanol) or oilseeds (e.g., biodiesel), as well as agricultural residues or purpose-grown biomass (lignocellulosic ethanol and advanced biofuels). Lignocellulosic agricultural residues are also used as low carbon liquid fuels. Bioethanol and biodiesel are in commercial production and use and are considered conventional crop-based fuels. All other fuels are considered unconventional within this report.

The Canadian unconventional crop-based low carbon liquid fuels incorporated in the Fuel LCA Modelling Tool are summarized in Table 40. Cereal grains are used for starch-based ethanol from fermentation, while oilseeds are processed and refined for oil-based fuels. Lignocellulosic residual biomass from these crops, primarily corn stover or wheat straw, may be used after additional processing for ethanol via fermentation[10].

Table 40. Summary of crop-based low carbon liquid fuel pathways including descriptions of fuel feedstock source, conversion processes, process energy carrier outputs, and expected end use to be modelled (feedstocks marked with an asterisk are not modelled in detail here).

Fuel	Feedstock	Conversion Process	End Use
Lignocellulosic Ethanol	Corn Stover Wheat straw	Enzymatic pretreatment C5 / C6 sugar fermentation Distillation	Transportation fuel
Hydrogen-Derived Renewable Diesel (HDRD)	Canola oil (Canadian) Palm oil (imported)	Hydro-processing Hydro-treatment	Transportation fuel
Renewable Biojet Fuel	Canola oil Used cooking oil	Hydro-processing Hydro-treatment	Transportation fuel

6.2 Cellulosic Ethanol

6.2.1 System Boundaries and Descriptions for Cellulosic Ethanol

Cellulosic ethanol can be produced from any source of cellulose such at grasses, trees and the unharvested parts of grain crops. It is of particular interest due to the low cost of cellulosic feedstocks; however, cellulose is more difficult to convert into fuels than the sugars and oils produced from grains and seeds.

Of particular interest as a cellulosic resource in Canada are corn stover and wheat straw. Corn stover and wheat straw are the above-grown portions of the plants without the grain. This includes stems, stalks, leaves and, in the case of corn, cobs. Both starch and cellulose are polymers of glucose (sugar). Starch is a linear polymer of glucose though it can sometimes be branching. Cellulose can form branching chains of glucose

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[10] Other routes, both biochemical and thermochemical, are also possible, though primarily at research or pilot scales.

as well as fairly long linear chains (particularly alpha cellulose). This combined with the 5 carbon sugar linkages not typically present in starch can make breaking down the structure of cellulose into sugars more energy intensive than that of starch. Hemicelluloses found in biomass cell walls are composed of both 5 and 6 carbon sugars which can also be converted to ethanol once these sugars are extracted from the biomass feedstock.

The differing structures of starch (linear) and cellulose (branching) are rooted in their different functions within the plant. Starch, which is, in the case of corn and wheat is primarily found in the grain at harvest, is an easily-accessible source of sugar for a growing seedling. Cellulose, the most abundant polymer of sugar on Earth, branches within the cell wall matrix of plants along with hemicelluloses and lignin to form the strong structural architecture of plants that allows them to grow tall. Thus, cellulose is not as easily accessible as a form of sugar feedstock as starch. Nevertheless, technologies have been developed to liberate the sugars from the cellulose in this matrix. Just like the glucose derived from starch, glucose from cellulose can be fermented to produce ethanol and used as a transportation fuel. The key difference between ethanol production from starch, like corn grain ethanol, and cellulosic ethanol, is not only in the feedstock, but in the addition of the pretreatment step in cellulosic ethanol production that liberates glucose from the cellulose, hemicelluloses and lignin in the cell wall. There are dozens of patented pretreatment techniques including adding acids or bases to the feedstock, exposing the feedstock to high temperature or pressure, mechanical separation and combinations of all of these (Sinistore, 2012).

The cellulosic ethanol fuels chosen to be included in the Fuel LCA Modelling Tool are summarized in Table 41. The primary difference between the two is the feedstock, which will affect the sugar yields and thus, the resulting ethanol, and potential co-product quantities.

Table 41. Summary of cellulosic ethanol fuel pathways including descriptions of fuel feedstock source, conversion processes, process outputs, and expected end use.

Fuel	Feedstock	Conversion Process	End Use
Cellulosic Ethanol	• Corn Stover	• Enzymatic pretreatment • C5 / C6 sugar fermentation • Distillation	• Transportation fuel
Cellulosic Ethanol	• Wheat Straw	• Enzymatic pretreatment • C5 / C6 sugar fermentation • Distillation	• Transportation fuel

Further descriptions of these fuels as well as an overview of the modelling approach and a summary of the data sources that were used to develop the life cycle inventory (LCI) for cellulosic ethanol are provided in the sections below.

Crop Residues

Cellulosic ethanol can be produced from a variety of feedstocks, but of primary interest to this analysis is the use of the crop waste corn stover or wheat straw. The difference between a crop residue and a crop waste is that a residue is deemed to have economic value, while a waste is deemed to have no economic value. Currently there is no commercial market for corn stover or wheat straw, thus production is based on information about the production of corn and wheat grain with expansion of the system boundaries to apply a burden to the corn stover and wheat straw to replace the nitrogen that is removed from the system when the stover and straw are harvested. The removal of this nitrogen requires increased inputs of nitrogen fertilizer in following years of production. Additionally, harvesting the corn stover and wheat straw requires an additional pass through the fields with a harvester. Therefore, the emissions from burning diesel to run this harvester are also assigned to the corn stover and wheat straw. These GHG emissions values for the additional N fertilizer and harvesting are given in Section 4.

6.2.2 Modelling Approach for Cellulosic Ethanol

The following sections provide a brief overview of the modelling approach for low carbon fuels, as well as discussion of the key methodological issues addressed in the modelling, the life cycle inventory data used, results and data gaps and limitations.

Development of Unit Process Building Blocks

The overall modelling approach for Milestone 3 is to develop unit processes to serve as building blocks for current and future modelling work in the Fuel LCA Modelling Tool. For cellulosic ethanol, the major building blocks of modeling will be the regional production of the two feedstocks, feedstock transport, pretreatment, fermentation, distillation and denaturation, fuel transport, blending and distribution, and combustion. Regional differences in feedstock production reflect different applications of inputs such as fertilizers and differing yields based on location. The major building blocks are illustrated in Figure 7.

Using this building blocks approach, even in cases where only literature data are available, or where no data is available, unit processes can still be developed and included as placeholders in the Fuel LCA Modelling Tool and can then be updated by tool users when data are available.

The modelling work in Milestone 3 relies heavily on fossil fuel unit processes that were developed in Milestone 2, including fuel inputs to machinery and equipment (e.g. diesel, natural gas, etc.) and transportation processes (e.g. trucks, rail, pipelines). These unit processes have been pulled from the ECCC Fuels database and incorporated into the low carbon fuel pathway models where needed. Systems outside of the system boundary of this analysis include on-farm and refinery equipment production, construction and decommissioning of ethanol refineries, and construction and decommissioning of combustion infrastructure. Significant modeling considerations include the inclusion or exclusion of direct and indirect land use change, allocation methods between grain and non-grain portions of the feedstock, potential applications of ethanol refinery co-coproducts and associated allocation, and combustion emissions of neat or blended fuels.

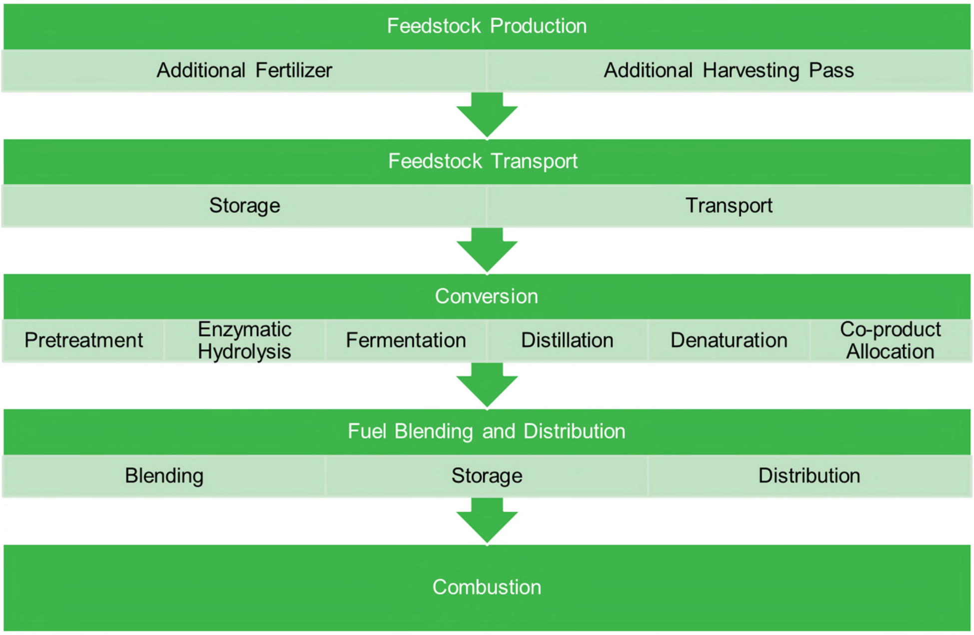

Figure 7: Building blocks of the cellulosic ethanol pathway

Regional Variation

Regional variations affect the yield and emissions from soils of different crops and thus the carbon intensities of the resulting fuels. Crop management practices that vary by region such as tillage practice, fertilizer and pesticide application rates will influence GHG emissions in addition to weather and soil variations over space and time. Since corn stover and wheat straw are treated as wastes in this study, they do not contribute to these regional variations in emissions from soils. Cellulosic fuel production has less influence from regionalization as the technologies for producing it do not need to vary by location. The major source of regional variation for fuel production is the electricity grid from which power is drawn for the conversion process. The distance which feedstocks must travel to reach a cellulosic ethanol facility will vary. Since, at the time of this writing, there are no commercial-scale corn stover or wheat straw cellulosic ethanol facilities, this distance has been based on assumptions about the locations of theoretical plants and will be described in greater detail in the description of transportation modeling. Regional nitrogen fertilizer requirements variation has been captured by modeling crop production by reconciliation unit (RU) which was developed by AAFC and ECCC as the smallest spatial unit at which activity data on crop production could be harmonized ((S&T)2 Consultants Inc., 2017c). With respect to background energy systems, electricity grid carbon intensities are available at a provincial level based on work completed in Milestone 2, as are some fuels (e.g. diesel), and have been incorporated into the unit processes available for modelling solid low carbon fuels.

Co-Product Allocation

Since the corn stover and wheat straw are treated as waste products from the production of corn grain and wheat in this study, they are not considered to be co-products of crop production. Therefore, these wastes do not receive burdens from the production of corn grain or wheat. Since corn stover and wheat straw are treated as wastes, none of the upstream GHG associated with corn and wheat cultivation are allocated between the corn product and corn stover co-product and the wheat grain and wheat straw co-product, respectively. Instead, GHG emissions from the production of ammonia fertilizer to replace the nitrogen in the stover and straw represent the burdens of the stover and straw removal. Additionally, GHG emissions from the combustion of diesel for the additional pass with a harvester to remove the stover and straw is included.

One point at which allocation can occur is at the cellulosic ethanol facility between the ethanol as the primary product and the remaining solids that consist of hemicelluloses and lignin as the co-product. Often, the fermentation can take advantage of the presence of five and six carbon sugars in the hemicelluloses, but some sugars generally remain. Moreover, the lignin cannot be fermented, but has some valuable applications. The most common use of the unused hemicelluloses fraction and the lignin co-products is to burn them for combined heat and power to fuel the ethanol production process. Often, excess electricity is generated as well, and this could be exported to the grid to offset electricity production by conventional means in that grid region.

The choice of allocation approach must be well-documented and transparent, including a clear rationale and sensitivity analysis to show the influence on the study results as it has been demonstrated to influence the ability of a fuel to meet a low carbon fuel policy (Kaufman, Meier, Sinistore, & Reinemann, 2010). For the electricity co-product of the cellulosic ethanol refinery, this excess electricity will provide a credit to the ethanol system for displacing the Canadian average grid. For the co-product electricity production from the ethanol refinery, the excess electricity will be exported to the grid and, therefore, is assumed to displace the emissions from grid electricity produced in Canada. A Canadian average electricity grid value was used because there are no specific locations in which corn stover or wheat straw cellulosic ethanol is being produced commercially in Canada. In the future, the user will be able to modify the co-products of ethanol production and the allocation method used, as well as the provincial electricity grid that is displaced. Note that the displacement of grid electricity with the electricity that could be produced by a future cellulosic ethanol plant is a documented method of allocation avoidance in the literature (Cronin, et al., 2017) (Kaufman, Meier, Sinistore, & Reinemann, 2010) (Sinistore, 2012). Furthermore, LCAs of sugarcane ethanol production apply the same displacement method to account for the excess electricity produced from the combustion of the bagasse co-product of sugar extraction from sugarcane (Wang, Han, Dunn, Cai, & Elgowainy, 2012). Double-counting of this electricity on the grid is avoided in the calculation of the CI of cellulosic ethanol because the background electricity grid mix used for Canada does not include electricity from cellulosic ethanol plants because none currently operate at a commercial scale in Canada.

Biogenic Carbon and Land Use Change

In remaining consistent with the Government of Canada’s policy on biogenic carbon, as shown in Canada’s National Inventory Report (Government of Canada, 2018), emissions of biogenic carbon from fermentation or combustion of cellulosic ethanol are assumed to be zero and therefore do not contribute to the GHG emissions of the fuel. The carbon balance into and out of the system have been evaluated to ensure masses balance and is well documented in the ethanol production literature (Humbird, et al., 2011). While removal of stover and straw can affect the long-term soil carbon balance this impact must be calculated in a spatially-explicit way that accounts for the specific climate, soil type, topography, land use, crop type, and crop rotation over time which require a dynamic parametric model (Sinistore, 2012).

Carbon emissions associated with direct land use change will be included in instances where feedstock production requires the conversion of land from existing use to bioenergy production. In the case of annual crops that are already produced in Canada, including corn and wheat, direct LUC is not included because a change in land use is not occurring. Indirect land use change (iLUC) is excluded from the carbon intensity calculations. Any changes in land management practices, such as the removal of the stover and the wheat straw from the fields, is included in this analysis.

6.2.3 Life Cycle Inventory for Cellulosic Ethanol

Agricultural Production

Since corn stover and wheat straw are classified as wastes in this study, no burdens from the agricultural production of corn or wheat grain are apportioned to the stover or straw. Instead, only the burden from additional ammonia fertilizer that must be added to the land as a result of the removal of N from the land in the stover and straw and the GHG emissions from an additional pass in the field to harvest the residues are included in the cellulosic ethanol CI. This is calculated according to the N content of the stover and straw and the amount of stover and straw used to make fuel. These data are summarized in Section 4.8.

Cellulosic Ethanol Production

Cellulosic ethanol differs from ethanol made from starch in five major ways. First, the cellulosic feedstock requires pretreatment to liberate the sugars from the cell walls of the plant material. Starch-based ethanol production often begins with mechanical breakdown such as in a hammer mill. The cellulosic feedstock may undergo some mechanical size-reduction, and then pretreatment. Many different technologies have been developed or are still under development to pretreat biomass. Some are specific to the type of biomass, while others are more general. Some of the only pilot-level cellulosic ethanol production facilities that have produced sizable quantities of cellulosic ethanol, such as the Iogen facility (Ontario, Canada) used dilute acid (DA) pretreatment of wheat straw to produce cellulosic ethanol in 2004 (Mupondwa, 2017).

The second difference is in the enzymatic hydrolysis. Starch-based production uses alpha-amylase to break the long polymers of glucose into shorter dimers and monomers of glucose, but these enzymes will not break the beta-glucosidic bonds in cellulose. Therefore, different enzymes, called cellulases, capable of breaking these bonds are used in cellulosic ethanol production. The third difference between starch-based and cellulosic ethanol production is in the sugars. The cell wall matrix is made of cellulose, hemicelluloses and lignin. Hemicelluloses are a class of compounds made from both 5- and 6-carbon sugars (C5 and C6, respectively, also known as pentoses and hexoses). Both C5 and C6 sugars are liberated from the hemicelluloses, while cellulose yields only glucose, a 6-carbon sugar. The lignin fraction does not provide sugar to the process. In fact, lignin demonstrates recalcitrance which means that after it is pulled apart from the cell wall matrix, it can stick back to the cellulose and hemicelluloses, blocking the sites where enzymes would act to break down the sugar polymers. One of the major reasons why different pretreatment methods give different sugar yields is the pretreatments method's proclivity to cause or prevent lignin recalcitrance.

The fourth difference is in fermentation. The organism used in fermentation of straight glucose (such as from starch) is *Saccharomyces cerevisiae* (commonly known as baker's yeast), but this organism will not convert the C5s from the cellulosic feedstock efficiently. Therefore, different organisms are used in cellulosic ethanol fermentation and result in different ethanol yields. In some cases, the enzymatic hydrolysis and fermentation are conducted together in something called simultaneous saccharification and co-fermentation because this can lead to higher yields of ethanol than separate stages. In this study, enzymatic hydrolysis and fermentation are modeled as separate steps.

After fermentation, the final steps for ethanol production are very similar in cellulosic ethanol as they are in starch ethanol with the exception of the co-product output. The output of the fermentation step is a distillation step to separate the ethanol from water and solids. The resulting ethanol is distilled, dehydrated and then denatured with gasoline in the starch-based ethanol process, (e.g., corn ethanol) the solids remaining are generally used as animal feed The solid fraction from the cellulosic ethanol process is high in carbon-rich lignin, which has a variety of potential uses. The most common use is burning the solids to provide fuel for the ethanol conversion process. Lignin has many other uses, but they are generally not commercially or economically viable. Wastewater is also produced from the distillation column and is treated on site. A process diagram that illustrates all of the stages of cellulosic ethanol production is provided in Figure 8 and additional details on each step are in the following sections.

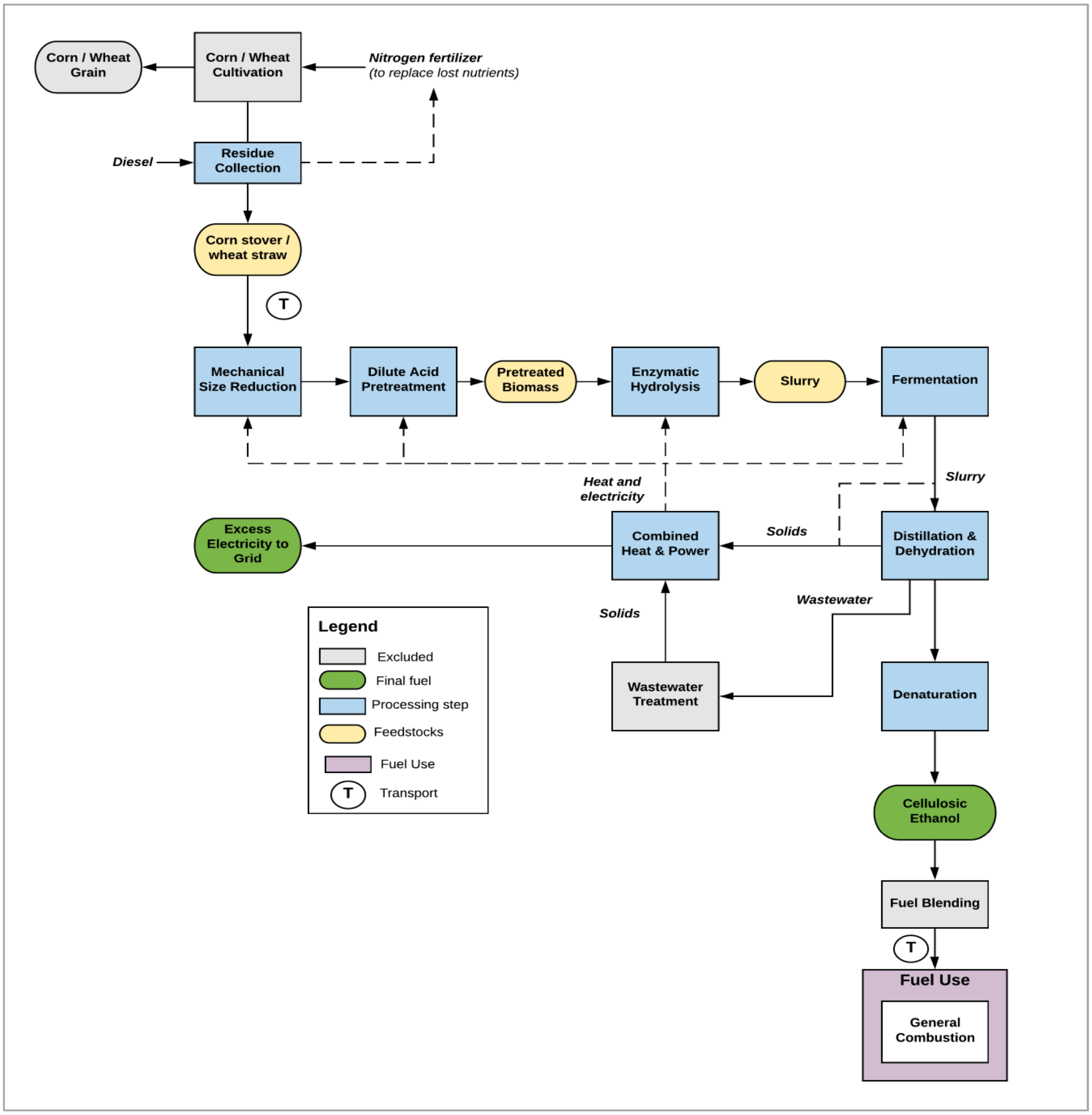

Figure 8: Process flow diagram of cellulosic ethanol production

Data for the cellulosic ethanol refinery from pretreatment through ethanol production and other process steps were obtained from a 2011 study by the National Renewable Energy Laboratory (Humbird, et al., 2011). This study assumed a plant size where 773,000 dry US tons (701,253 MT) of corn stover are processed per year, with a 76% theoretical ethanol yield or 79 gallons of ethanol per dry ton of corn stover. This gives an annual yield of 61,067,000 gallons of ethanol or 231,163,741 liters. This analysis follows the same assumptions as the NREL study. Wheat straw has a different sugar composition from corn stover, most notably, no sucrose and higher glucan (cellulose) and xylan fractions which yield more fermentable sugar per kilogram of feedstock input. Wheat straw also, however, has a higher lignin fraction than corn stover, and as discussed above, lignin has been demonstrated to inhibit enzymatic hydrolysis and fermentation of sugars (Saha, Iten, Cotta, & Wu, 2005). This study modeled the wheat straw to ethanol pathway with the same conversion efficiency assumptions for the sugars yielded from corn stover in the NREL study, but with lower sugar content from wheat straw. Therefore, the yield of ethanol from the same quantity of wheat straw (773,000 dry US tons) will be 57,508,000 gallons of ethanol or 217,694,000 liters, with a 72% theoretical yield of 74 gallons of ethanol per try ton of wheat straw which is in line with the findings of other studies on wheat straw conversion to ethanol with dilute acid pretreatment and enzymatic hydrolysis given the lower sugar yield of wheat straw compared to corn stover (Novy, Longus, & Nidetzky, 2015).

Dilute Acid Pretreatment

The pretreatment step in cellulosic ethanol production liberates glucose from the cellulose, hemicelluloses and lignin in the cell wall. There are dozens of patented pretreatment techniques including adding acids or bases to the feedstock, exposing the feedstock to high temperature or pressure, mechanical separation and combinations of all of these (Sinistore, 2012).

One of the most common and well-developed methods of pretreatment is called dilute acid (DA) (Cronin, et al., 2017; Mupondwa, 2017). In this method dilute sulfuric acid (H_2SO_4) is combined with the biomass at high temperature for a short time. After this process is complete, ammonia (NH_4) is added to the pretreated slurry to raise its pH from approximately 1 to 5 in preparation for enzymatic hydrolysis. Data for the DA pretreatment were obtained from a 2011 study by the National Renewable Energy Laboratory (Humbird, et al., 2011). Specifics about the conversion efficiencies between biomass to sugar and sugar to ethanol are provided in Appendix A. Overall inputs to the pretreatment, enzymatic hydrolysis, and fermentation are summarized in Table 42. Life cycle inventory data for these inputs, other than the feedstock, have been obtained from GREET (Wang, Han, Dunn, Cai, & Elgowainy, 2012).

Enzymatic Hydrolysis and Fermentation

The 2011 NREL study also specified the inputs used for fermentation (Humbird, et al., 2011). As noted above, a different organism is used in fermentation in cellulosic production. The assumption in this study is the use of recombinant *Zymomonas mobilis*. The conversion efficiencies for C6 and C5 sugars to ethanol are 90% and 80%, respectively, when DA pretreatment is used. Note that different pretreatment methods lead to different ethanol yields from C6 and C5 sugars. Enzymatic hydrolysis occurs in a continuous reactor in which the pretreated biomass is combined with the cellulases and heated. This process results in a partially-hydrolyzed slurry. The hydrolysis is completed in batches in parallel bioreactors, after which the resulting slurry is cooled. In preparation for fermentation, the cooled slurry is inoculated with the microorganism. The complete residence time is approximately five days. Cellulose enzymes can be produced on site or purchased from outside vendors. The NREL study models on-site enzyme production. While some technologies have an added step to separate C5 and C6 sugars for fermentation in different reactors, the NREP study assumes co-fermentation.

Table 42: Inputs to pretreatment, hydrolysis and fermentation

Inputs
Feedstock (corn stover or wheat straw)
Sulfuric acid (93%)
Ammonia
Corn steep liquor
Diammonium phosphate
Sorbitol
Glucose
SO_2
Enzyme nutrients
Caustic
Lime
Cooling tower chemicals
Fresh water

Distillation, Dehydration and Denaturation, Co-product and Wastewater Treatment

The 2011 NREL study also specified the inputs used for distillation, dehydration and denaturation. Distillation uses a distillation column (similar to that used in fossil liquid fuel separation) to separate ethanol, water and residual solids. The distillation can only remove 95% of the water, however, and the remaining azeotropic mixture must be dehydrated to 99.5% ethanol with a vapor-phase molecular sieve which adsorbs water and allows ethanol to pass through. The solids that result from distillation are rich in lignin and contain some sugars. As noted above, the most common treatment for solids is to burn them in a combined heat and power (CHP) facility to generate heat and power for the cellulosic ethanol production. Distillation also results in liquid wastewater which must be treated. Since this water is rich in sugars, it is anaerobically digested to produce methane which can be combusted with the lignin solids to produce additional process heat and power for ethanol production. This combustion often results in an excess of electricity that can be exported to the local grid. As noted in the allocation section, allocation is avoided for this co-product allocation by applying system expansion or displacement of grid electricity. The total amount power generated by the CHP for the ethanol plant size modelled is 41MW per year according to the NREL study (Humbird, et al., 2011). This results in a total production of 1,437,833 GJ per year, while the annual demand of electricity from the ethanol plant is 873,830 GJ. The difference is assumed to be exported to the grid to displace the average Canadian grid carbon intensity on a MJ to MJ basis.

Feedstock and Fuel Transport and Fuel Blending and Distribution

An overview of the modelling for feedstock and fuel transport is provided in Appendix B. One important factor in the fuel blending is that, before leaving the ethanol production facility, the ethanol is denatured with 2 to 5% conventional gasoline. Later blending to fuel grade results in common blends of E10 (10% ethanol and 90% gasoline) and E85

(85% ethanol and 15% gasoline). Although, E85 is no longer used in Canada (there are no more pumps available for this fuel blend), increasingly, E15 blends are becoming mainstream in the US and may be used in Canada in the future. This scope, however, considers only the unblended ("neat") fuel production.

The transportation of feedstocks and final cellulosic ethanol will be done largely by truck and rail. In modelling this transport, we will use the truck and train unit processes that were created in Milestone 2 to capture the upstream and combustion emissions associated with these modes of transport.

Cellulosic Ethanol Combustion

At the point of combustion, all of the carbon in the cellulosic ethanol fuel is biogenic carbon, not fossil carbon. Therefore, the combustion of this carbon results in no net addition to the fossil emissions from the fuel. In this way, the combustion emissions from burning cellulosic ethanol (neat, unblended) are zero. Methane and other types of GHG emissions are possible from the combustion of cellulosic ethanol, and these emissions are dependent upon the combustion efficiency of the engine in which the fuel is burned and the blend of the fuel being combusted. As a placeholder, emissions factors for methane (0.14 g/L, 6.03E-06 kg/MJ) and nitrous oxide (0.022 g/L, 9.47E-07 kg/MJ) were used from Canada's National Inventory Report (Government of Canada, 2018) for bioethanol. These emissions factors from the NIR are in turn based on conventional gasoline. Characteristics of ethanol (regardless of feedstock) are given in Table 43.

Table 43. Characteristics of ethanol (Government of Canada, 2018).

Fuel	Application	Density	High Heating Value	Carbon Content	Biogenic CO_2 (g/L fuel)
Ethanol	Transportation fuel	789.3kg/m^3	29.67 kJ/g	52.14%	1,508

6.2.4 Carbon Intensity Results for Cellulosic Ethanol

Carbon Intensities

The carbon intensities of corn stover and wheat straw ethanol, total and per life cycle phase, are given in Table 44. Since all of the heat and electricity requirements for the facility are met by the CHP fed by the co-products of ethanol production and those products contain only biogenic carbon, the GHG impacts are assumed to be zero for the CHP. Note that the many of the GHG emission in this table are non-zero, but the values are less than 1% of the impact so are reported as zero. This may affect sums due to rounding.

The primary inputs to the other phases of ethanol production are chemicals used to treat the biomass (e.g., sulfuric acid) and the on-site production of the cellulase for enzymatic hydrolysis. Previous studies have excluded cellulase production in some cases due to lack of available data on production (Kaufman, Meier, Sinistore, & Reinemann, 2010). The GHG emissions from on-site cellulase production were sourced from GREET. It is clear from the results below that the credit provided for the displacement of Canadian grid electricity is a significant driver of the overall CI of the cellulosic ethanol as it offsets all of the emissions from both agricultural and industrial production. The same credits are applied in well-established LCAs of sugarcane ethanol production for the electricity co-product produced from burning bagasse for process heat and power with excess exported to the local grid (Wang, Han, Dunn, Cai, & Elgowainy, 2012). Previous studies acknowledge that it is unrealistic to assume that no electricity is exported to the grid and have also used a variety of assumptions for the amount of electricity exported to the grid (Kaufman, Meier, Sinistore, & Reinemann, 2010). If the fraction of low-carbon renewable energy increases over time, the credit to the cellulosic ethanol system will decrease. Without this credit, the CIs for corn stover and wheat straw ethanol would be 31 and 32 gCO_2e/MJ HHV, respectively which is significantly higher than the negative values in the table below. In addition, it is higher than the cradle to gate impacts of fossil fuels, but due to the biogenic carbon content, lower than the impacts of combusted fossil fuels. Given that there are no commercial scale cellulosic ethanol facilities currently operating in Canada, this electricity credit is not accounted for in the modeling of the Canadian energy grid.

Feedstock production contributes more than 1% to the total CI, but phases such as feedstock and fuel transportation and distribution do not contribute significantly (<1%) to the overall cellulosic ethanol CI from either corn stover or wheat straw. The uncertainty assessment for corn stover and wheat straw ethanol is provided in Table 45. The uncertainty is presented based on the uncertainty in the underlying data. The 2.5% heading indicates the interquartile range of uncertainty and the 97.5% heading indicates the 1.5x interquartile range. SD stands for standard deviation, CV is the coefficient of variance and SEM is the standard error of the mean. This uncertainty analysis of corn stover ethanol indicates that the range of CIs are between -44 and 15 gCO_2e/MJ corn stover ethanol HHV, indicating great potential variability in the result. Similarly for wheat straw ethanol, the uncertainty analysis reveals large variability, with the range of potential CIs between -33 and 18 gCO_2e/MJ.

Table 44: Carbon intensities of corn stover and wheat straw ethanol, total and by life cycle phase

Life Cycle Phase	g CO_2e/ MJ corn stover ethanol HHV	g CO_2e/ MJ wheat straw ethanol HHV
Corn Stover Production	2.5	-
Wheat Straw Production	-	1.9
Feedstock Transport	1.9	2.0
Pretreatment	2.0	2.1
CS Enzymatic Hydrolysis & Fermentation	24	-
WS Enzymatic Hydrolysis & Fermentation	-	25
Distillation & Dehydration	0.0	0.0
Wastewater Storage Utilities	0.0	0.0
Lignin Combustion Exported Electricity Credit	-38	-41
Fuel Distribution	0.8	0.8
Fuel Combustion	0.4	0.4
Total	**-6.4**	**-8.8**

Note that some values appear to be zero due to limiting the number of significant figures in these results to 2.

Table 45: Uncertainty analysis for corn stover and wheat straw ethanol

Cellulosic ethanol, from corn stover (gCO_2e/MJ corn stover ethanol HHV)							
CI	**Mean**	**Median**	**SD**	**CV**	**2.50%**	**97.50%**	**SEM**
-6.9	-9.1	-7.6	18.8	-161%	-43.8	15.0	0.00033
Cellulosic ethanol, from wheat straw (gCO_2e/MJ wheat straw ethanol HHV)							
CI	**Mean**	**Median**	**SD**	**CV**	**2.50%**	**97.50%**	**SEM**
-8.8	-10.8	-8.5	17.6	-164%	-32.5	17.5	0.00039

6.2.5 Data Gaps and Limitations for Cellulosic Ethanol

In preparation of the report and CI values for cellulosic ethanol, a number of data gaps and limitations have been highlighted to inform further research, including:

- Lack of a Canadian-specific process model for cellulosic ethanol production which required the use of a well-cited US study: Note that the processing conditions and technology for cellulosic ethanol are not anticipated to vary based on the location of the ethanol plant (e.g., Canada versus the US), but more so based on the company-specific technology and intellectual property involved in the production. If there are companies with viable technologies applying to produce cellulosic ethanol at the commercial scale (e.g., 25 million gallons/year or more), then their technology could be used to improve the modeling of a Canadian cellulosic ethanol production scenario.
- Spatially explicit crop modeling to determine GHG emissions, such as N_2O, from soils and soil carbon change (e.g., emission or sequestration over time) as a result of stover and straw removal and the addition of N fertilizer replacements: The IPCC Tier 2 equations were used to approximate GHG emissions from the application of nitrogen fertilizers, which is an acceptable and well-documented method, but further precision could be added with spatially explicit crop modeling which did not fit within the scope or timeline of this project.
- Spatially explicit crop modeling to determine the soil organic carbon changes over time due to the removal of corn stover and wheat straw;
- Documentation on the input of diammonium phosphate (DAP) per kg of feedstock treated during enzymatic hydrolysis and fermentation were not detailed enough in the NREL process document to determine the exact quantities required.

6.3 Hydrogenation-Derived Renewable Diesel (HDRD)

6.3.1 System Boundaries and Descriptions for HDRD

Hydrogenation-Derived Renewable Diesel (HDRD) is a type of renewable or “green” diesel that is produced from the same feedstock as biodiesel using a different process. The resulting fuel composition is similar to petroleum diesel with primarily saturated straight chain (C12-C18) hydrocarbons. While biodiesel, is produced by transesterification and produces glycerol as a co-product, HDRD is produced by hydro-processing with the co-products of bio-based propane, carbon monoxide (CO) and carbon dioxide (CO_2). HDRD is produced from a wide variety of bio-based feedstocks, though the most common are animal fats and wastes (e.g., tallow and yellow grease) and vegetable oils (e.g., canola, soy and palm). The yield from production does not vary significantly based on the type of feedstock used (Natural Resources Canada, 2012).

HDRD can be made from fats and oils as they are composed primarily of triglycerides which have a glycerol backbone and three fatty acids. It is the aliphatic chain length and saturation degree of the fatty acids that determines the properties of the final HDRD product such as cold flow, density and energy content. Unlike biodiesel, HDRD can be produced from a wider-range of feedstocks because HDRD produces fully-saturated hydrocarbons that are not susceptible to oxidative instability and, during hydro-processing, free fatty acids can be converted to paraffin while in biodiesel processing, these acids can react with alkali catalysts creating soaps. HDRD can also take advantage of existing refining technologies used in conventional refineries to desulfurize fractional distillates like diesel oil. HDRD is currently produced in commercial quantities by Neste in Porvoo, Finland, Rotterdam, The Netherlands, and Singapore as well as by REG in Geismer, Louisiana, in the United States, but not yet at the commercial scale in Canada (McCormick & Alleman, 2016).

The HDRD processes that will be included in the Fuel LCA Modelling Tool are summarized in Table 46. The primary difference between the two is that HDRD from canola oil will be produced in Canada and HDRD from palm oil is imported as finished fuel.

Table 46. Summary of HDRD fuel pathways including descriptions of fuel feedstock source, conversion processes, process outputs, and expected end use.

Fuel	Feedstock	Conversion Process	End Use
HDRD (Canada-produced)	• Canola oil (Canadian)	• Hydro-processing • Hydro-treatment	• Transportation fuel
HDRD (imported)	• Palm oil	• Hydro-processing • Hydro-treatment	• Transportation fuel

Further descriptions of these fuels as well as an overview of the modelling approach and a summary of the data sources that were used to develop the life cycle inventory (LCI) for HDRD are provided in the sections below.

Crops

HDRD can be produced from a wide variety of feedstocks, but of primary interest to this analysis is the use of the canola oil from canola grown in Canada and imported HDRD from palm oil. Canola oil production is an established market in Canada, thus production is based on information about the current production of canola in Canada. Palm oil is not produced in Canada and, currently, all of the HDRD that is made from palm oil for use in Canada is imported. Therefore, the evaluation of palm oil-derived HDRD will be based on literature on the production of HDRD from palm oil outside of Canada.

As part of the modelling in Milestone 3 to develop default pathways for HDRD from canola oil, production has been modeled at a provincial level, from planting through to harvesting the canola and extracting the oil. The LCI data from this work will be used to model the feedstock production for canola oil by allocating the upstream GHG emissions associated with canola cultivation between the canola oil product and the remaining meal co-product. This allocation has been done based on the energy content of the primary oil product and the remaining meal co-product.

Canola

Canola oil is a co-product of canola cultivation. The oil is pressed from the seeds of the canola plant leaving behind the protein meal. Feedstock production for canola is based on allocation of the GHG emissions from Canadian canola cultivation between oil and other products. The upstream agricultural data have been developed in a separate modelling effort within M3 and are summarized in Section 4. Detailed LCI data on Canadian canola production broken down by province have been compiled by Dr. Nathan Pelletier based on reports from the Canadian Roundtable for Sustainable Crops (http://sustainablecrops.ca/). These data include GHG emissions associated with activities from cradle to farm gate, including fuel inputs, chemical inputs (i.e. fertilizers, pesticides), and on-field emissions associated with crop management practices (e.g. tillage, fallowing, etc.).

Palm oil

Oil palm is cultivated in tropical climates in places like Malaysia, Central Africa and Brazil. Since the import of HDRD from palm oil is primarily from Singapore, the Malaysian production has been selected as most representative of the palm oil used in HDRD production. Cultivation of palm for palm oil yields not only the palm oil, but also the palm kernels (from which palm kernel oil can be made) and biogas production from palm oil mill effluent (POME). Additionally, from the production of palm oil, fibers, shells and empty fruits are produced and burned for process heat and power at the palm oil facility (Usitalo, et al., 2014).

Since palm oil-derived HDRD is not produced in Canada, this report gives only a final carbon intensity (CI) for palm oil based on literature sources for palm HDRD produced in the Singapore region based on a 2014 study of renewable diesel from palm oil (Usitalo, et al., 2014).

6.3.2 Modelling Approach for HDRD

The following sections provide a brief overview of the modelling approach for HDRD fuels, as well as discussion of key methodological issues to be addressed in the modelling.

Development of Unit Process Building Blocks

The overall modelling approach for Milestone 3 is to develop unit processes to serve as building blocks for current and future modelling work in the Fuel LCA Modelling Tool. For HDRD the major building blocks of modeling with be the regional production of the canola oil in Canada or palm oil in Malaysia, feedstock transport, pretreatment, catalytic de-waxing, hydro-treatment, fuel transport, blending and distribution, and combustion. Regional differences in feedstock production reflect different applications of inputs such as fertilizers and differing yields based on location. The major building blocks are illustrated in Figure 9.

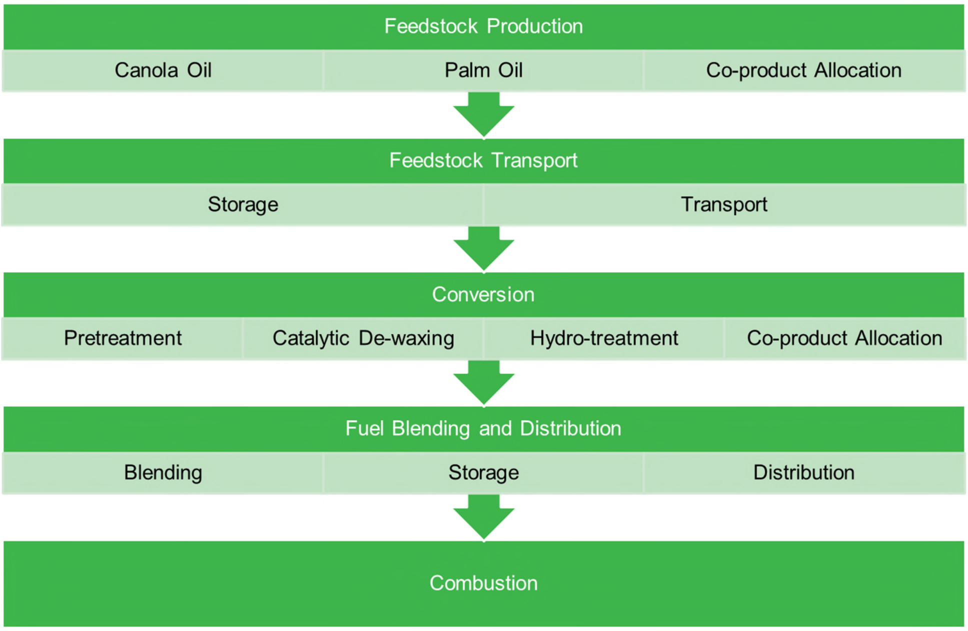

Figure 9: Building blocks of the HDRD pathway

Regional Variation

Regional variations affect the yield and emissions from soils of different crops and thus the carbon intensities of the resulting fuels. Crop management practices that vary by region such as tillage practice, fertilizer and pesticide application rates will influence GHG emissions in addition to weather and soil variations over space and time. HDRD fuel production has less influence from regionalization as the technologies for producing it do not need to vary by location. The major source of regional variation for fuel production is the electricity grid from which power is drawn for the conversion process. The distance which feedstocks must travel to reach an HDRD production facility will also vary.

Since at the time of this writing, there are no commercial-scale canola oil to HDRD production facilities in Canada, this distance is based on assumptions about the locations of theoretical plants and is described in greater detail in the description of transportation modeling.[11] Regional crop production variation is captured by modeling crop production by reconciliation unit (RU) which was developed by AAFC and ECCC as the smallest spatial unit at which activity data on crop production could be harmonized ((S&T)2 Consultants Inc., 2017c). With respect to background energy systems, electricity grid carbon intensities are available at a provincial level based on work completed in Milestone 2, as are some fuels (e.g. diesel), and has been incorporated into the unit processes available for modelling low carbon fuels.

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[11] According to data provided by ECCC on the imported and domestically-produced biodiesel and HDRD in Canada, no HDRD was produced in Canada between 2013 and 2017 though it was imported from The Netherlands, Singapore, and the United States.

Co-Product Allocation

There is a major point of co-product allocation between the canola oil and the rest of the canola seed also called meal or cake.

In Milestone 1 and 2 it was established through discussions with ECCC that upstream carbon intensity would be allocated to co-products according to energy content. Efforts have been made to use this approach consistently in modelling work for Milestone 3; however, using the building blocks approach for the Fuel LCA Modelling Tool, the capability to choose different allocation approaches will be incorporated in the tool. In canola production, all of the inputs to the agricultural system are required in order to produce both the oil and the other parts of the seed. Allocation between the oil and meal align with the method used in the biodiesel from canola oil section in using energy allocation. Allocation by mass and energy content of the respective products is possible and is consistent with the ISO 14044 guidelines on allocation as they represent a physical relationship between products. Using displacement would require identifying a suitable product that would be displaced by the production of the meal which is not as straightforward as it is with, for example, the co-product allocation in corn grain ethanol between the ethanol and the distillers' grains. In that case, the distillers' grains can displace the production of other types of animal feed. In the case of canola oil, the co-product canola protein meal is commonly fed to animals today, regardless of the use of the canola oil. It is hard to justify that the production of this meal displaces other products in the market because there is an established market for canola oil meal. In this study, energy content was chosen to allocate between the canola oil and the meal. In the future model that is built, the user will be able to modify the co-product allocation method used.

Another point at which allocation can occur is at the HDRD production facility between the HDRD as the primary product and the bio-propane, CO and CO_2 co-products. It is unlikely that the CO or CO_2 would be sold as valuable coproducts, but the bio-propane can be used as a fuel to displace conventional propane, therefore a displacement method has been used to account for this co-product. In this case, the production of the bio-propane displaces the GHG emissions from the production (not including combustion) of conventional Canadian propane as calculated in Milestone 2. A 2017 study of biopropane extraction from HDRD or renewable diesel facilities found that, of the twelve facilities operating in the world, only one could be confirmed to be producing bio-propane as of 2017 (Johnson E. , 2017).

Biogenic Carbon and Land Use Change

In remaining consistent with the Government of Canada's policy on biogenic carbon, as shown in Canada's National Inventory Report (NIR) (Government of Canada, 2018), biogenic carbon emitted from the combustion of the HDRD and its coproduct biopropane are assumed to be zero, and therefore, will not contribute to the GHG emissions of the fuel. The carbon balance into and out of the system has been evaluated to ensure mass balance.

Carbon emissions associated with direct land use change have been included in instances where feedstock production requires the conversion of land from existing use to bioenergy production. This is covered in Section 4. In the case of annual crops that are already produced in Canada, including canola, direct LUC is not included because land use change is not occurring. Indirect land use change (iLUC) is excluded from the carbon intensity calculations. Any changes in land management practices as a result of crop production for biofuels is included in this analysis, but these crop management changes have not been observed for the production of canola oil for HDRD compared to production of canola oil for other uses. Information on the land use change that may be occurring for palm oil-based HDRD are lacking and are a data gap of this study.

6.3.3 Life Cycle Inventory for HDRD

Canola

Agricultural Production and Oil Extraction

Canola (*Brassica napus*), also called rapeseed, is a crop commonly grown in Canada as an edible oil and for biodiesel production. Feedstock production for canola is based on allocation of the GHG emissions from Canadian canola cultivation between oil and other products such as canola meal. The energy allocation to canola oil is 72%. The inputs and outputs from canola production are provided in Section 4 on agricultural production.

Canola oil is extracted from seeds via crushing and solvent-extraction and yields about 40% to 45% oil and the remaining matter (55% to 65%) is protein meal or cake used as animal feed. The extraction process begins with cleaning the seeds and pre-conditioning them, then rolling the seeds, cooking and pressing them to yield some oil, then extracting additional oil from the seed press-cake with hexane. The oil then goes through solvent removal and toasting processes (Newkirk, 2009). Per tonne of canola oil produced, 114.5 kWh of electricity, and 2.34 GJ of natural gas are required ((S&T)2 Consultants Inc., 2010).

Palm Oil

Agricultural production

The palm plant (*Elaeis guineensis*) is cultivated in various tropic regions of the world. For this work, cultivation is assumed to occur in Malaysia, which has a tropical climate. Cultivation inputs, such as fertilizers and pesticides, as well as diesel and electricity follow the methods in a 2014 study on the carbon footprint of HDRD from palm oil cultivation (Usitalo, et al., 2014). Furthermore, from this same study, the amount of extracted oil, co-products and combustion of POME for oil extraction were used. Increasing cultivation of palm for oil (in fuel and other applications) is reported to be causing increases in logging of forests, conversion of rainforests and peatlands and decreases in the production of other crops such as rubber and coconut (Usitalo, et al., 2014). While this paper did consider iLUC, it did not calculate the direct land use change (dLUC) values. These land use change emissions are significant and have been considered within the scope of this study. The land use change considered in the study can occur from shifting land from peat soils, tropical mineral soils or from tropical grasslands to oil palm production. The dominant land cover in Malaysia is dense forest which is a combination of the peat swamp forest and tropical forest (approximately 60% total), but data are lacking to delineate between peat swamp forest and tropical rainforest (Geography of Malaysia, 2019; Butler, 2019). As of 2012, palm oil covered 15.4% of the total land area in Malaysia, which makes it difficult to determine if all palm oil harvested for production of HDRD in Singapore for export to Canada induced land use change or if some portion of that palm oil came from existing palm plantations that have been in production for 20 years or more (Palm oil production in Malaysia, 2019). Therefore, both land use change factors from peat swamp forest and from tropical forest are considered in this study with the more conservative approaching being to take the higher of the two factors.

Palm oil extraction begins with the separation of the fruit from the fiber. The fruit is then pressed to produce crude palm oil, which is clarified into filtered palm oil. As mentioned above, since palm oil-derived HDRD is not produced in Canada, this report gives only a final carbon intensity (CI) for palm oil based on literature sources for palm HDRD produced in the Singapore region based on a 2014 study of renewable diesel from palm oil (Usitalo, et al., 2014). No detailed modeling of the palm oil production is included in this study.

HDRD Production

HDRD differs significantly from biodiesel, though they share some common feedstocks. HDRD uses hydrotreatment with steam and hydrogen to create a fuel with a higher cetane number (70 to 90, compared to biodiesel at 45 to 55), higher energy content (44 MJ/kg LHV compared to 39 MJ/kg LHV) and by not using transesterification (Natural Resources Canada, 2012). Both fuels must meet the relevant ASTM and CGSB specifications for blending, which includes certain cetane ratings. The production technology considered in this study is only a stand-alone process, and does not include co-refining with a crude oil refinery. HDRD production steps include pretreatment of the feedstock oil to remove impurities, then proceeds to hydrotreatment with hydrogen and steam. The products are the HDRD, bio-propane, CO, and CO_2. For the hydrotreating process, hydrogen must be generated, likely by steam methane reforming, and the wastewater that is generated must be treated. A process diagram that illustrates all of the stages of HDRD production is provided in Figure 10 and additional details on each step are in the following sections.

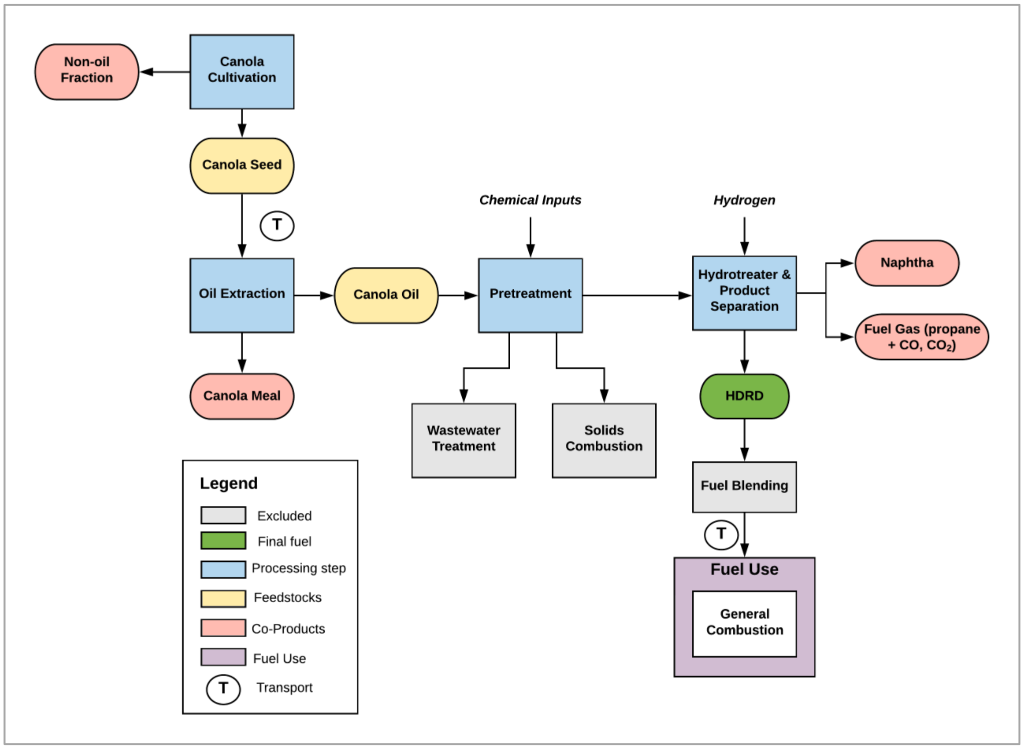

Figure 10: Process flow diagram of HDRD production

Data for the canola-based HDRD refinery from pretreatment through fuel production and other process steps were obtained entirely from literature sources including: a 2012 study published by Natural Resources Canada, and a 2014 study on the production of renewable diesel (HDRD) from rapeseed oil (a variant of canola oil), a renewable fuels roadmap for sustainable biomass feedstock and a published journal article on emissions parameters and energy consumption for renewable diesel (Natural Resources Canada, 2012; Usitalo, et al., 2014; Antares Group, Inc., 2010; Miller & Kumar, 2013). The Natural Resources Canada study identifies canola oil as a significant source of domestic feedstock for potential HDRD production in Canada as canola oil is not currently being used in Canada to produce HDRD.

Pretreatment

HDRD production begins with a feedstock pretreatment to prepare the feedstock for hydroprocessing. The quality of the feedstock determines if and to what extent pretreatment is required. Pretreatment is intended to address the potential alkali metals, phospholipids, and metalloids that could be present in the feedstock and which would reduce the efficacy of the hydroprocessing catalysts. Pretreatment can include the hydrogenation of the fatty acid chains to reduce the number of double bonds in the chain, but this is not included in this process modeling. The pretreatment requires inputs of water, chemicals, heat and electricity with outputs of pretreated oil, some losses, wastewater and solid waste. Table 47 summarizes the inputs to pretreatment for which data were available. The solid waste can be used for energy production. Wastewater undergoes wastewater treatment. Data on the precise amount of chemicals and other inputs other than electricity and natural gas per mass of oil treated or HDRD produced were lacking in the literature (Miller & Kumar, 2013).

Table 47: Inputs to HDRD pretreatment

Inputs	Amount	Unit
Electricity	2.2	kWh/MT seed
Steam	74.3	kg steam/kg seed
Chemicals	unknown	unknown

Hydro-treatment

The pretreated oil is then ready for hydrotreatment. During hydrotreatment, steam and hydrogen are added to help convert the triglycerides in the vegetable oil to saturated straight-chain hydrocarbons. Since, this reaction is exothermic, the addition of heat is not necessary. The reaction actually produces 160 BTU of heat per pound of oil treated (Antares Group, Inc., 2010). the additional demand for electricity is also very low. The inputs to HDRD hydrotreatment per liter of HDRD produced are provided in Table 48 (Miller & Kumar, 2013). The life cycle inventory data on hexane production were also sourced from literature (Miller & Kumar, 2013).

Table 48: Inputs to HDRD hydrotreatment

Inputs	Amount	Unit
Hydrogen	0.020	kg/L HDRD
Electricity	0.080	kWh/L HDRD
Natural Gas	5.6	MJ/ L HDRD
Hexane	0.22	kg/L HDRD

The co-products of this process include bio-naphtha, bio-propane, CO and CO_2. Since the carbon dioxide produced from this process originates from biogenic carbon sources, it is not considered an overall emission of fossil carbon. Hydrogen is a key input to the production of HDRD; therefore, hydrogen production must be considered as a part of the overall HDRD production process. Hydrogen is often produced by using a steam reformer. The hydrogen production via on-site reforming with liquid truck delivery CI was sourced from this Milestone 3 work (see Section 9) for use in the HDRD production CI calculation.

The conversion efficiency of oil to fuel is approximately 98% on an energy basis. Hydrogen consumption can be calculated based on a percentage of the feedstock input weight as 1.5 the weight percentage of the feedstock. The production of light hydrocarbons (e.g., bio-propane) is about 3.5 wt% of the mass of the input feedstock. Water consumption is estimated to be minimal for the hydrotreatment process (Antares Group, Inc., 2010).

Feedstock and Fuel Transport and Fuel Blending and Distribution

The transport of feedstock to HDRD producers and the transport of the final HDRD product to end users is described and modelled in the biodiesel section of this report to be in line with the transport of canola and canola oil for biodiesel production and in the distribution of finished fuels that are similar to diesel. Only the production of the neat or unblended fuel is considered in this report.

The transportation of feedstocks and final fuel will be done largely by truck and rail. In modelling this transport, the truck and train unit processes that were created in Milestone 2 to capture the upstream and combustion emissions associated with these modes of transport are used.

Combustion

At the point of combustion, all of the carbon in the HDRD fuel is biogenic carbon, not fossil carbon. Therefore, the combustion of this carbon results in no net addition to the fossil emissions from the fuel. In this way, the combustion emissions from burning HDRD (neat, unblended) are zero. Methane and other types of GHG emissions are possible from the combustion of HDRD, and these emissions are dependent upon the combustion efficiency of the engine in which the HDRD is burned and the blend of the fuel being combusted. As a placeholder, emissions factors for methane (0.14 g/L, 3.96E-06 kg/MJ) and nitrous oxide (0.082 g/L, 2.32E-06 kg/MJ) were used from Canada's National Inventory Report (Government of Canada, 2018) for biodiesel. Characteristics of HDRD (regardless of feedstock) are given in Table 49.

Table 49. Characteristics of HDRD (Natural Resources Canada, 2012; Argonne National Lab, 2018; Usitalo, et al., 2014).

Fuel	Application	Density (g/gal)	High Heating Value (MJ/kg)	Low Heating Value (MJ/kg)	Carbon Content (wt%)	Biogenic CO_2 (g/gal fuel)
HDRD	Transportation fuel	2,835	44.6	43.5	84.9%	2,400

6.3.4 Carbon Intensity Results for HDRD

Carbon Intensity of Canola Oil HDRD

The carbon intensity of canola oil HDRD, total and per life cycle phase, are given in Table 50. The hydrogen production and steam requirement for hydrotreatment are the large drivers of GHG emissions to HDRD production. After hydrogen production, feedstock production is the most significant driver, especially if seed and oil production are taken together. Transportation of seed, oil and final fuel are not large drivers of GHG emissions. Note that the GHG emissions credit for the production of biopropane is not zero, but the negative value is in the 4th decimal place and, for the purpose of consistency, results are reported with 2 significant figures. Thus, it is clear that the credit provided by the co-production of propane is not a significant source of GHG emissions savings. The uncertainty assessment for canola oil HDRD is provided in Table 51. The uncertainty is presented based on the uncertainty in the underlying data. The 2.5% heading indicates the interquartile range of uncertainty and the 97.5% heading indicates the 1.5x interquartile range. SD stands for standard deviation, CV is the coefficient of variance and SEM is the standard error of the mean. This uncertainty analysis of canola oil HDRD indicates that the range of CIs are between 51 and 59 g CO_2 eq/MJ HDRD HHV. This indicates that, given the uncertainty in the background data, the uncertain range is plus 9% to minus 6%.

Other studies have been conducted on HDRD or renewable diesel from palm oil, but many involve LUC, economic allocation and other aspects that are inconsistent with the system boundaries and scope of this assessment which make them not directly comparable. These values range from between 24 and 50 gCO_2e/MJ HDRD LHV (Johnson E. , 2017). Sources of differences between the CI for canola oil HDRD in this study and other studies include the canola oil production (this study uses canola oil production Canada and the other uses rapeseed oil production in Europe), transportation and distribution assumptions, the use of the Canadian grid electricity CI and the Canadian natural gas CI for inputs and propane CI for the displacement credit. Since most studies of this kind do not quantify any type of uncertainty, it is not possible to compare the uncertainty ranges to that of other studies.

Table 50: Carbon intensity of canola oil HDRD total and by life cycle phase

Stage	Amount	Unit
Canola seed	16	g CO_2 eq./MJ
Canola oil production	9.7	g CO_2 eq./MJ
Pretreatment	0.5	g CO_2 eq./MJ
Hydrotreatment	29	g CO_2 eq./MJ
Co-product propane credit	-1.9	g CO_2 eq./MJ
Fuel transport	0.5	g CO_2 eq./MJ
Combustion	0.7	g CO_2 eq./MJ
Total	**54**	g CO_2 eq./MJ

Table 51: HDRD from canola oil, average per MJ uncertainty (g CO_2 eq./MJ HDRD HHV)

Carbon Intensity	Mean	Median	SD	CV	2.50%	97.50%
54	57.9	54.3	19.2	33.1%	32.8	106

Carbon Intensity of Palm Oil HDRD

Based on the results of the 2014 study of the carbon impacts of palm oil HDRD produced in Singapore, the GHG emissions from 1 MJ (HHV) of palm HDRD are 24 g CO_2e/MJ HHV of HDRD without the inclusion of land use change (Usitalo, et al., 2014). This includes emissions from palm production, oil extraction, transportation, HDRD production, but does not include iLUC. When LUC is included, based on the same study, the CI rises to between 270 and 460 g CO_2e/MJ HHV of HDRD assuming that all of the palm oil produced to make the HDRD came from land converted from tropical forest land and tropical peaty swamp land, respectively. The most conservative approach would be to use the conversion from tropical peaty swamp land as it results in the highest CI. Since this is a large source of emissions, it should be clarified with producers of palm oil if land use change is occurring for the production of all Malaysian palm oil used to make HDRD in Singapore that is exported to Canada, and what the previous land use type was for that palm oil plantation.

A study by Usitalo, et al., 2014 study notes, however, that palm oil extraction does not result in significant GHG emissions if energy for extraction is derived from palm fibers and shells and if methane that results from POME production is collected. If POME methane is not collected, it can be a large source of emissions, therefore, it should be clarified with producers how POME is treated to confirm that this CI is reflective of the palm oil HDRD used in Canada.

6.3.5 Data Gaps and Limitations for HDRD

In preparation of the report and CI values for HDRD, a number of data gaps and limitations have been highlighted to inform further research, including:

- The process design documents used for this study did not enumerate the process chemical inputs to pretreatment phase of HDRD so they could not be accounted for. It is recommended to find another source for these data.
- Data on the exact type and amounts of solvents used in canola oil extraction are lacking.
- Information on the direct land use change that may be occurring and the resulting GHG emissions from this dLUC for palm oil-based HDRD are lacking.
- There is lack of consensus in the literature about the exact process energy and material inputs to the production of HDRD. It is recommended that these data be updated with data from an operational commercial facility should one be cited in Canada.
- The CI for palm oil HDRD is based on literature values only. It is recommended that data on production be collected from palm oil HDRD facilities providing fuel to Canada so that it can be modeled, or requiring the facilities to conduct life cycle assessments on their fuels and provide documentation of their calculated CIs.
- Palm oil extraction does not result in significant GHG emissions if energy for extraction is derived from palm fibers and shells and if methane that results from POME production is collected. If POME methane is not collected, however, it can be a large source of emissions. Therefore, it is recommended that ECCC clarify with palm oil HDRD producers how POME is treated to confirm that the CI reported in this study is reflective of the palm oil HDRD used in Canada.
- There is a lack of information about the source location of palm production for the HDRD produced in Singapore and exported to Canada. Information about the source location of palm production includes confirming that production is occurring in Malaysia, the age of the palm plantations (i.e., plantations that have been in production for 20 years or more) and, if the plantation has been in production for less than 20 years, the type of land use that preceded the palm plantation (i.e., whether it was tropical rainforest, peat swamp forest or another land use type). This lack of information was the determining factor for the conservative assumption that all palm for HDRD produced in Singapore and exported to the US was produced in Malaysia from land that was recently converted from tropical peaty swamp land.

6.4 Renewable Biojet Fuel

Biojet fuel is aviation fuel made from renewable, biomass-derived raw materials. Currently the primary production process for biojet is the hydroprocessed esters and fatty acids (HEFA) process which has already been done at commercial scale to produce renewable diesel and produces biojet as a co-product. The biojet product from this process is synthetic paraffinic kerosene (SPK). For other production pathways such as biomass gasification and Fischer-Tropsch (FT) synthesis, there are currently no operating facilities in Canada (Doyletech Corporation, 2018).

The HRJ process involves catalytic conversion of renewable oils into alkanes in a process that is comparable to conventional hydroprocessing of crude oil. Potential feedstocks for HRJ include vegetable oils from oilseed crops, UCO, tallow, and algal oils. The feedstock oils are subject to a high temperature catalytic hydrodeoxygenation process which produces mainly renewable diesel, with biojet, naphtha, and light hydrocarbons (i.e. propane) as typical co-products (Doyletech Corporation, 2018).

6.4.1 System Boundaries and Descriptions for Biojet Fuel

Two pathway templates were developed for biojet fuel for the Fuel LCA Modelling Tool, including biojet produced from used cooking oil (UCO) and from canola oil via hydroprocessing (HEFA, or hydroprocessed renewable jet fuel (HRJ)).

UCO is a mixture of used vegetable oils and fats produced by restaurants and other institutional kitchens. UCO can be pretreated and converted to biojet fuel using a hydroprocessing step that yields HRJ fuel and a number of other fuel co-products. Canola oil is derived from processing and extraction of Canadian canola oilseed crops, as described in Section 5.3. From a life cycle perspective, the production of biojet fuel from UCO originates with the production and use of cooking oils in restaurants; however, UCO from these sources is considered a waste product and no GHG emissions associated with upstream activities are attributed to them, which is consistent with a number of other LCAs of biodiesel from yellow grease (California Environmental Protection Agency, 2009) ((S&T)2 Consultants Inc., 2012) (Chen, et al., 2018) (University of Toronto, 2019). The system boundary for the life cycle carbon intensity of biojet fuel from UCO therefore begins at the restaurant gate, and includes transport of UCO, pre-treatment, HRJ fuel production, distribution, and combustion (Figure 11). For biojet from canola oil, the system boundary begins with average Canadian cultivation of canola oilseed crops.

6.4.2 Modelling and Life Cycle Inventory for Biojet from UCO

The system boundary for biojet fuel from UCO is shown in Figure 11. The basic model building blocks for this process include:

- Transport of UCO from restaurants to the processing plant;
- Pre-treatment of UCO;
- Biojet fuel production via hydroprocessing;
- Biojet fuel distribution; and
- Biojet fuel combustion.

After biojet fuel production, the life cycle activities and resulting GHG emissions for distribution are assumed to be the same as for crop-based biodiesel pathways. The life cycle inventory and modelling considerations for biojet from UCO are outlined below.

Transport of Used Cooking Oil (UCO)

For the Canadian average template developed for biojet fuel from UCO, it is assumed that UCO is transported by truck from restaurants within the same province as the biojet conversion plant over an average distance of 100 km. Users of the Fuel LCA Modelling Tool can modify this transport distance and/or add additional transport modes and distances to align with more specific supply chain configurations in the future.

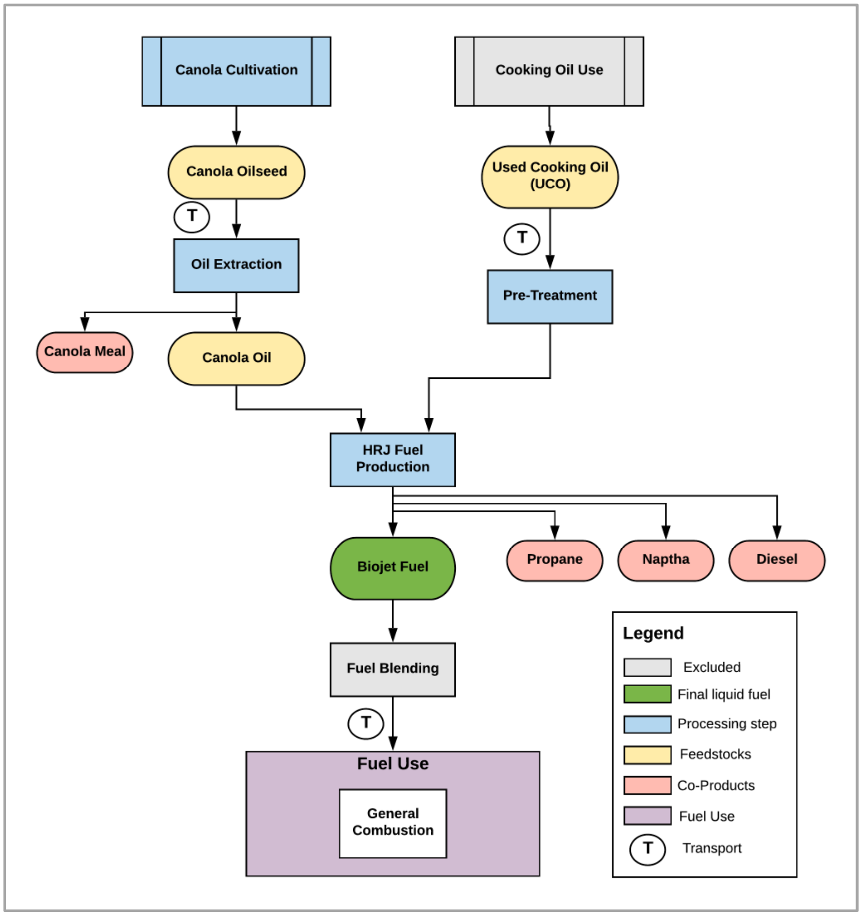

Figure 11. System boundaries for production of biojet fuel from UCO and canola oil.

UCO Pre-Treatment

Pretreatment of raw UCO is required to remove solid particles and the oil is then heat treated to remove moisture. The mass balance and energy intensity of pre-treating UCO for biojet fuel conversion were derived from a 2014 Canadian (Chu, 2014). These data were developed to represent the Canadian context, although are largely based on literature data and are not based on primary data collection. The mass balance and energy inputs for pre-treating 1 tonne of UCO are shown in Table 52.

Table 52. Mass balance and energy inputs for pretreatment of 1 tonne of UCO for biojet conversion.

Pretreatment	Amount
Inputs	
UCO (kg)	1,000
Transport of UCO to plant (tkm)*	100
Natural gas (MJ)	1,134
Electricity (kWh)	126.8
Outputs	
Pretreated UCO (kg)	1,000

*****UCO is assumed to be transported 100 km*

Conversion of UCO to Biojet

After pre-treatment, UCO is processed through a hydroprocessing conversion process. The process converts the oils into fuels by using a reaction with hydrogen and energy to bring the process to the required temperature and pressure. A summary of the inputs and outputs of converting UCO to biojet is provided in Table 53. In addition to SPK, the conversion process yields a number of co-product fuels. This allocation was done according to the energy content of the outputs, resulting in 60.3% of the emissions associated with biojet conversion being allocated to the biojet fuel.

Table 53. Mass balance and material and energy inputs for conversion of UCO to biojet fuel via hydroprocessing (Chu, 2014).

	Amount
Inputs	
UCO (kg)	1,000
Hydrogen (kg)	26.3
Electricity (kWh)	2,835
Natural gas (MJ)	73
Outputs	
Propane (MJ)	3,120
Naphtha (MJ)	6,100
SPK (MJ)	23,100
Diesel (MJ)	6,000

**Note – The energy contents of the co-products include: propane – 50.2 MJ/kg; naphtha – 46.2 MJ/kg; SPK (biojet) – 46.3 MJ/kg; diesel – 45.8 MJ/kg.*

The GHG emissions associated with production and use of hydrogen, electricity, and natural gas were obtained from the Fuel LCA Modelling Tool based on previous modelling work in Milestone 2 and Milestone 3.

Biojet from UCO Distribution and Combustion

It is assumed that after conversion of biojet fuel from UCO that all other life cycle activities related to distribution are equivalent to those of the crop-based biodiesel pathways modeled in Milestone 3 (see Section 5.3). Due to the biogenic nature of the carbon emissions from biojet combustion, they are excluded from the CI calculations. Methane and other types of GHG emissions are possible from the combustion of biojet fuel, and these emissions are dependent upon the combustion efficiency of the engine in which the fuel is burned and the blend of the fuel being combusted. As a placeholder, emissions factors for methane (2.2 g/L, 5.81E-05 kg/MJ) and nitrous oxide (0.23 g/L, 6.07E-06 kg/MJ) were used from Canada's National Inventory Report (Government of Canada, 2018) for fossil aviation fuel.

6.4.3 Carbon Intensity of Biojet from UCO

The carbon intensity results for biojet fuel from UCO are summarized in Table 54. The CI for biojet from UCO is approximately 22 g CO_2 eq./MJ, which is 74% lower than fossil aviation fuel (86 g CO_2 eq./MJ). The reduction in CI is largely due to the biogenic nature of the carbon emissions from biojet fuel. The primary contributor to the life cycle GHG emissions is the biojet conversion process. These emissions are due to the use of hydrogen and natural gas. Hydrogen was assumed to be produced by SMR of fossil natural gas and has a relatively high CI. Feedstock transport and fuel distribution make relatively small contributions, as does pretreatment of the UCO.

Table 54. Carbon intensity results for biojet fuel produced from UCO, expressed in g CO_2 eq. per MJ of biojet energy.

Life Cycle Stage	Amount	Unit
Feedstock Transport	0.3	g CO_2 eq./MJ
Pretreatment of UCO	2.4	g CO_2 eq./MJ
HRJ Conversion	16	g CO_2 eq./MJ
Distribution	0.5	g CO_2 eq./MJ
Combustion	3.2	g CO_2 eq./MJ
Total	**22**	**g CO_2 eq./MJ**

6.4.4 Modelling and Life Cycle Inventory for Biojet from Canola Oil

The system boundary for biojet fuel from canola oil is shown in Figure 11. The basic model building blocks for this process include:

- Cultivation of canola oilseed crops;
- Extraction of canola oil;
- Transport of canola oil feedstock to biojet processing plant;
- Biojet fuel production via hydroprocessing;
- Biojet fuel distribution; and
- Biojet fuel combustion.

After biojet fuel production, the life cycle activities and resulting GHG emissions for distribution are assumed to be the same as for biojet from UCO. The life cycle inventory and modelling considerations for biojet from canola oil are outlined below.

Canola Cultivation and Oil Extraction

Cultivation and processing of the canola oil feedstock was based on the same cultivation and oil extraction processes modeled for canola biodiesel, as described in Section 5.3.

Transport of Canola Oil to Biojet Facility

For the Canadian average template developed for biojet fuel from canola oil, it is assumed that the canola oil is transported by truck from processors within the same province as the biojet conversion plant over an average distance of 100 km. Users of the Fuel LCA Modelling Tool can modify this transport distance and/or add additional transport modes and distances to align with more specific supply chain configurations in the future.

Conversion of Canola Oil to Biojet

The conversion of canola oil to biojet fuel via hydroprocessing is essentially the same process as for UCO, except that pretreatment is not required, and the inputs and yield of the process are slightly different than for UCO due to the different properties of canola oil (Han J. , Elgowainy, Cai, & Wang, 2013a). The inputs and outputs for biojet fuel conversion of canola oil are shown in Table 55. In addition to SPK, the conversion process yields a number of co-product fuels. Relative to the UCO conversion process, renewable diesel is not targeted in the canola oil conversion process and thus there is a greater yield of biojet fuel. This allocation was done according to the energy content of the outputs, resulting in 81.1% of the emissions associated with biojet conversion being allocated to the biojet fuel.

Table 55. Mass balance and material and energy inputs for conversion of UCO to biojet fuel via hydroprocessing.

	Amount
Inputs	
Canola oil (kg)	1,000
Hydrogen (MJ)	4,444
Electricity (kWh)	61
Natural gas (MJ)	7,782
Outputs	
Propane (MJ)	4,575
Naphtha (MJ)	3,418
SPK (MJ)	34,262

**Note – The energy contents of the co-products include: propane – 50.2 MJ/kg; naphtha – 46.2 MJ/kg; SPK (biojet) – 46.3 MJ/kg.*

Biojet from Canola Oil Distribution and Combustion

It is assumed that after conversion of biojet fuel from canola oil that all other life cycle activities related to distribution are equivalent to those of the crop-based biodiesel pathways modeled in Milestone 3 (see Section 5.3). Due to the biogenic nature of the carbon emissions from biojet combustion, they are excluded from the CI calculations. Methane and other types of GHG emissions are possible from the combustion of biojet fuel, and these emissions are dependent upon the combustion efficiency of the engine in which the fuel is burned and the blend of the fuel being combusted. As a placeholder, emissions factors for methane (2.2 g/L, 5.81E-05 kg/MJ) and nitrous oxide (0.23 g/L, 6.07E-06 kg/MJ) were used from Canada's National Inventory Report (Government of Canada, 2018) for fossil aviation fuel.

6.4.5 Carbon Intensity of Biojet from Canola Oil

The carbon intensity results for biojet fuel from canola oil are summarized in Table 56. The CI for biojet from canola is approximately 49 g CO_2 eq./MJ, which is 43% lower than fossil aviation fuel (86 g CO_2 eq./MJ). The reduction in CI is largely due to the biogenic nature of the carbon emissions from biojet fuel. The primary contributor to the life cycle GHG emissions is the biojet conversion process. These emissions are due to the use of hydrogen and natural gas. Hydrogen was assumed to be produced by SMR of fossil natural gas and has a relatively high CI. Production of the canola oil feedstock is also a significant contributor to the CI, and is a notable contrast to biojet from UCO where the waste feedstock only requires transport and pretreatment and makes a much smaller contribution to life cycle GHG emissions.

Table 56. Carbon intensity results for biojet fuel produced from canola oil, expressed in g CO_2 eq. per MJ of biojet energy.

Life Cycle Stage	Amount	Unit
Feedstock Production	14	g CO_2 eq./MJ
Oil Extraction	8.6	g CO_2 eq./MJ
HRJ Conversion	23	g CO_2 eq./MJ
Distribution	0.5	g CO_2 eq./MJ
Combustion	3.2	g CO_2 eq./MJ
Total	**49**	**g CO_2 eq./MJ**

6.4.6 Uncertainty

Uncertainty analysis was conducted for Canadian average biojet fuel from UCO and canola oil using Monte Carlo analysis. Results of the uncertainty analysis are shown in the violin plots in Section 12 and discussed relative to the uncertainty of other low carbon fuels in that section. Below in Table 57 the key results of the uncertainty analysis for both types of biojet fuel are summarized.

Table 57. Uncertainty analysis for biojet fuel produced from UCO and canola oil. Results based on Monte Carlo analysis with a confidence interval of 95%.

Final CI	Mean	Median	SD	Min (2.5%)	Max (97.5%)
Biojet fuel, from UCO, average {CA}					
22.0	22.4	22.0	3.90	16.0	31.2
Biojet fuel, from canola oil, average {CA}					
49.0	52.6	49.6	16.1	30.8	91.5

The uncertainty range for biojet from UCO is much tighter than for canola oil, with canola oil showing a potentially high upper range. This is due to the inherent uncertainty in modelling agricultural systems which increases the range of potential results.

6.4.7 Data Gaps and Limitations for Biojet Fuel

The primary limitation for modelling biojet fuel production in Canada is the lack of operating data for biojet conversion systems. More primary, Canadian-specific data on the material and energy outputs of hydroprocessing and other biojet conversion technologies would improve the robustness of the CI calculations. This would also allow for users of the Fuel LCA Modelling Tool to link conversion processes with other existing feedstocks in the tool that are commonly used for biojet fuel production (e.g. soybean, camelina, etc.).

7. Waste-Derived Low Carbon Liquid Fuels

7.1 Introduction to Waste-Derived Low Carbon Liquid Fuels

Waste-derived fuels are of interest because the feedstock itself carries no burden and because the use of waste for fuel diverts it from landfills, reducing the burden on land. While there are many different wastes that might be treated and several different treatment methods, the fuels considered for consideration here included those currently in use and one with high potential as a low carbon substitution.

Table 58. Summary of waste-derived liquid fuel pathways including descriptions of fuel feedstock source, conversion processes, process energy carrier outputs, and expected end use modelled.

Fuel	Feedstock	Conversion Process	End Use
Waste-Derived Biodiesel	Beef tallow Yellow grease	Rendering/purification Transesterification Refining	Transportation fuel
MSW-Derived Ethanol	MSW (yard trimmings)	Pretreatment Fermentation Ethanol recovery	Transportation fuel

7.2 Beef Tallow Biodiesel

Inedible fats and yellow grease are used in the production of chemicals, and increasingly used as feedstocks in the production of biodiesel and HDRD. These feedstocks can also be co-processed in a petroleum refinery. For example, West Coast Reduction is selling these feedstocks to BP Cherry Point refinery in Washington State, and more recently, to Parkland Refinery in Burnaby, B.C. When Canada’s biodiesel industry started out, inedible fats and yellow grease were the predominant feedstocks used to produce fatty acid methyl esters (FAME). Over time, canola oil and, to a lesser extent, soy oil have replaced some of these waste fats and greases as the waste-derived biodiesel product has poorer cloud point properties. There is growing interest in alternatives to crop-based biodiesel feedstocks such as yellow grease from used cooking oil (UCO) and tallow from animal rendering (Han, Elgowainy, & Wang, 2013b). At present, biodiesel from these sources makes up a small proportion of Canadian biodiesel production, with tallow biodiesel accounting for less than 1% of total biodiesel production in 2017, and biodiesel from yellow grease accounting for just under 7% of total 2017 production (Wolinetz et al. 2019). Domestic production of these alternative types of biodiesel is currently concentrated in specific areas, mostly in Ontario and Québec (Wolinetz, Hein, & Moawad, 2019). A substantial amount of waste fats and greases is exported to other countries for biofuel production. Domestic use of these feedstocks could increase with co-processing at petroleum facilities or new HDRD facilities.

7.2.1 System Boundaries and Descriptions for Tallow Biodiesel

The template developed for tallow biodiesel in the Fuel LCA Modelling Tool is for biodiesel produced from beef tallow. Beef tallow is produced from the rendering of by-products from cattle slaughter. Cattle slaughter is a process to produce beef as well as a number of co-products and by-products including animal hides, offal, animal by-products, and other non-marketable wastes (Han, Elgowainy, & Wang, 2013b). The animal by-products are processed in rendering plants and this process results in the production of tallow, animal bone/meat meal, and wastewater. Beef tallow can then be used as input to biodiesel production.

From a life cycle perspective, the production of biodiesel from beef tallow originates with the rearing and slaughtering of livestock; however, the slaughterhouse by-products are considered a waste product and no GHG emissions associated with upstream activities are attributed to the by-products. This is a well-established modelling convention in the LCA literature (Han, Elgowainy, & Wang, 2013b) ((S&T)2 Consultants Inc., 2012) (Chen, et al., 2018). The system boundary for the life cycle carbon intensity of tallow biodiesel therefore begins at the slaughterhouse gate, and includes transport of animal by-products, rendering, upgrading of tallow, biodiesel conversion, distribution, and combustion (Figure 12).

Modelling and Life Cycle Inventory

The system boundary for biodiesel from beef tallow is shown in Figure 12. The basic model building blocks for this process include:

- Transport of slaughterhouse by-products to the rendering plant;
- Rendering of animal by-products to produce beef tallow;
- Upgrading of beef tallow (e.g. polishing, refining, and bleaching)[12]
- Transport of beef tallow from the rendering plant to the biodiesel production plant;
- Biodiesel production (for feedstock with high free fatty acids);
- Biodiesel distribution; and
- Biodiesel combustion.

After biodiesel production, the life cycle activities and resulting GHG emissions are assumed to be the same as for crop-based biodiesel pathways. The life cycle inventory and modelling considerations for biodiesel from beef tallow are outlined below.

Transport of Slaughterhouse By-Products

There are a limited number of certified slaughterhouses for cattle in Canada, and they are primarily located in Ontario (6 facilities), Alberta (6 facilities), and Quebec (3 facilities) (Agriculture and Agri-Food Canada, 2019), which are the provinces where Canadian beef production is centered. There are considerably more animal rendering and processing plants in Canada, but they are also heavily concentrated in Ontario, Quebec, and Alberta (CBC News, 2012). Data for 2017 indicate that all biodiesel produced from tallow was produced in Québec (Wolinetz, Hein, & Moawad, 2019).

We developed a Canadian average pathway for biodiesel production from beef tallow using average supply chain transport distances and average Canadian energy inputs. Transport of animal by-products from the slaughterhouse to the rendering plant is assumed to be by truck, and that slaughterhouse by-products are only transported to in-province rendering plants over an average distance of 100 km. Users of the Fuel LCA

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[12] Different biofuel processes have different tallow specifications. For example, co-processing operations prefer bleached tallow.

Modelling Tool will be able to modify transport distances and energy sources to reflect more specific conditions for biodiesel from beef tallow in the future.

Animal By-Product Rendering

The mass balance and energy intensity of animal by-product rendering are potentially quite variable depending on the facility ((S&T)2 Consultants Inc., 2012) (Chen, et al., 2017). For example, the energy required for the rendering process may vary considerably depending on the moisture content of the incoming animal by-products and the type of energy used may vary depending on system configuration at the rendering plant. Work by S&T2 Consultants for the GHGenius tool and for the California low carbon fuel program has included some Canadian tallow rendering data; however, more recent updates in the GREET tool indicate that previous values for energy use for beef tallow rendering have been significantly overestimated (Chen, et al., 2017). Although the data in GHGenius were developed to represent the Canadian context, these data are from the early-2000's and changes in industry practices may have led to changes in yield and energy intensity over time. As such, we have used the mass balance and energy inputs for production of 1 kg of tallow from rendering of animal by-products from the latest update to GREET, which are representative of average US production (Table 59).

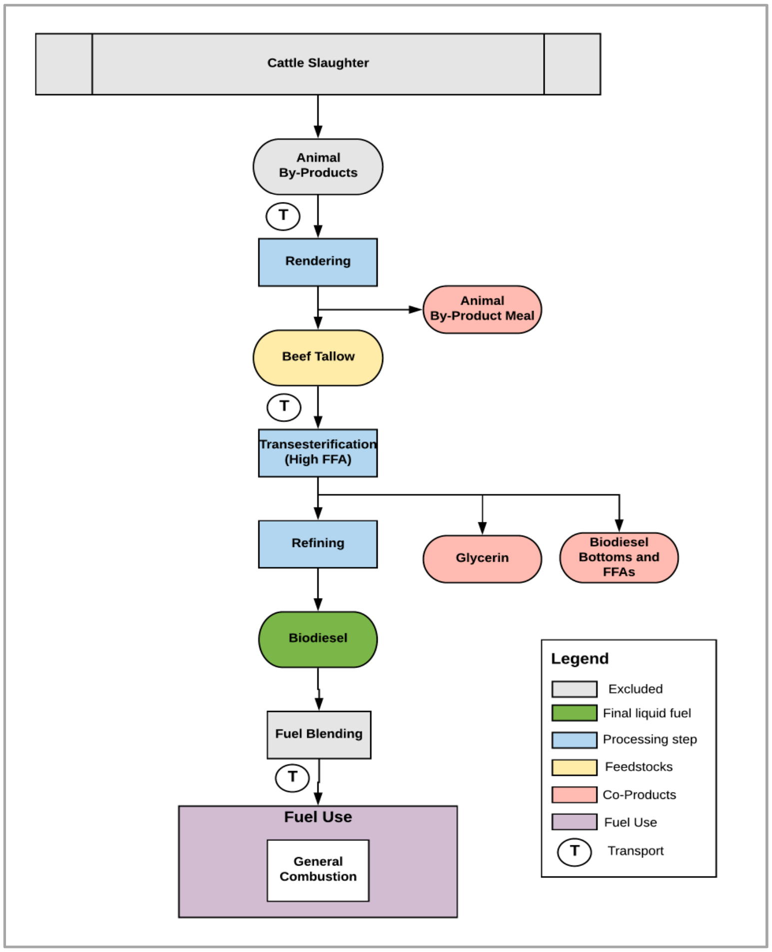

Figure 12. System boundaries for production of biodiesel from beef tallow.

The rendering process produces tallow as well as meat and bone meal and water/vapours from the cooking process. The cooking vapours are a waste stream and are excluded from the CI calculations. The emissions associated with rendering must therefore be allocated between the tallow and the meal. This allocation has been done according to the energy content of the co-products, which is estimated as 37.6 MJ/kg for tallow and 16.9 MJ/kg for meal (Denafas, Buinevicius, Urniezaite, Puskorius, & Rekasius, 2004). This results in allocation of 73% of the emissions to beef tallow and 27% to the meat and bone meal.

Table 59. Mass balance and energy inputs for rendering of 1 kg of beef tallow from slaughterhouse by-products in an average US facility (Chen, et al., 2017).

Rendering	Amount
Inputs	
Animal by-products (kg)	3.55
Transport of by-products to plant (tkm)**	0.5
Natural gas (MJ)	3.95
Residual fuel oil (MJ)	2.36
Fat/grease (MJ)	1.83
Electricity (kWh)	1.16
Co-Products	***Amount***
Tallow (kg)	1.0
Meat and bone meal (kg)	0.81
Wastes	***Amount***
Cooking vapours (kg)	1.74

**The allocated inputs are based on the energy content of the rendering products, including tallow at 37.6 MJ/kg, and animal by-product meal at 16.9 MJ/kg. Based on these energy content values, 73% of the emissions associated with the rendering process are allocated to the beef tallow.*

***Animal by-products are assumed to be transported 100km*

Transport of Tallow to Biodiesel Plants

For the Canadian average template developed for beef tallow biodiesel, it is assumed that beef tallow is transported by truck from rendering plants within the same province as the biodiesel plant over an average distance of 100 km. Users of the Fuel LCA Modelling Tool can modify this transport distance and/or add additional transport modes and distances to align with more specific supply chain configurations in the future.

Conversion of Tallow to Biodiesel

Biodiesel facilities that use waste feedstocks such as tallow do not require an oil extraction step, but do require a pre-treatment step to remove water, high levels of free fatty acids, and other impurities (University of Toronto, 2019). For the Fuel LCA Modelling Tool, the LCI for a biodiesel conversion process for feedstocks with high FFAs was used to reflect the additional pre-treatment required for tallow and the increased energy and material inputs to this process relative to converting vegetable oils with lower fatty acid contents (Chen, et al., 2018). These data are for an average US biodiesel conversion process and are used to represent average Canadian production. A summary of the inputs and outputs of converting beef tallow to biodiesel is provided in Table 60. Unlike conversion of vegetable oil feedstocks, this conversion process also yields significant amounts of biodiesel heavies and FFAs, such that the conversion process impacts were allocated between biodiesel, glycerol, heavies, and FFAs. This allocation was done according to the energy content of the outputs, as per Chen et al. (2018), resulting in 86% of the emissions associated with biodiesel conversion being allocated to the biodiesel.

The GHG emissions from electricity production are based on the 2016 average Canadian grid mix.

Table 60. Mass balance and material and energy inputs for production of biodiesel from beef tallow in an average US facility (Chen, et al., 2018).

Biodiesel Production	Amount (per kg of biodiesel)	Amount (per MJ of biodiesel)
Inputs		
Beef tallow (kg)	1.1	0.0274
Natural gas (MJ)	2.163	0.0538
Electricity (kWh)	0.0864	0.00215
Biodiesel distillation bottoms (MJ)	0.0131	0.000326
Diesel (MJ)	0.0235	0.00059
Methanol (kg)	0.11	0.00274
Sulfuric acid (kg)	0.0001	2.49E-06
Hydrochloric acid (kg)	0.0036	8.96E-05
Sodium methylate (kg)	0.0052	0.00013
Sodium hydroxide (kg)	0.0007	1.74E-05
Potassium hydroxide (kg)	0.0006	1.49E-05
Nitrogen gas (kg)	0.0275	0.00068
Phosphoric acid (kg)	0.0003	7.46E-06
Citric acid (kg)	0.0004	9.96E-06
Outputs		
Glycerol (kg)	0.0815	0.00203
Biodiesel distillation bottoms (kg)	0.0243	0.000605
Fatty acids (kg)	0.0771	0.001919
Biodiesel (kg)	1	0.0337

**Note – The energy contents of the co-products include (Chen et al. 2018): glycerol - 18.56 MJ/kg; biodiesel distillation bottoms – 39.47 MJ/kg; fatty acids – 39.47 MJ/kg. The energy content of biodiesel is 29.67 MJ/kg.*

Biodiesel Distribution and Combustion

It is assumed that after conversion of tallow to biodiesel that all other life cycle activities related to distribution and combustion are equivalent to those of the crop-based biodiesel pathways modeled in Milestone 3 (see Section 5.3), and that final energy content of the biodiesel is equivalent to conventional biodiesels (29.67 MJ/kg).

7.2.2 Carbon Intensity of Biodiesel from Beef Tallow

The carbon intensity values for biodiesel from beef tallow are summarized in Table 61. The CI for beef tallow biodiesel is approximately 21 g CO_2 eq./MJ, which is 79% lower than fossil aviation fuel (100 g CO_2 eq./MJ). The reduction in CI is largely due to the biogenic nature of the carbon emissions from biojet fuel. The primary contributor to the life cycle GHG emissions is the rendering of beef tallow from slaughterhouse by-products, followed by biodiesel production. The rendering process is energy-intensive and will vary depending on the nature of the incoming by-products and the efficiency of the system. No impacts are attributed to the upstream rearing and slaughter of animals, so this feedstock CI is attributed entirely to the rendering process. Transport of feedstock and fuel make relatively minor contributions to life cycle GHG emissions.

Table 61. Carbon intensity results for biodiesel produced from beef tallow, Canadian average, expressed in g CO_2 eq. per MJ of biodiesel energy.

Life Cycle Stage	Amount	Unit
Feedstock Production	10	g CO_2 eq./MJ
Feedstock Transport	0.5	g CO_2 eq./MJ
Biodiesel Production	5.4	g CO_2 eq./MJ
Transport & Distribution	0.8	g CO_2 eq./MJ
Combustion	4.4	g CO_2 eq./MJ
Total	**21**	**g CO_2 eq./MJ**

7.3 Yellow Grease Biodiesel

7.3.1 System Boundaries and Descriptions for Yellow Grease Biodiesel

The default pathway for biodiesel produced from yellow grease in the Fuel LCA Modelling Tool is for biodiesel produced from used cooking oil (UCO) feedstock. UCO is a mixture of used vegetable oils and fats produced by restaurants and other institutional kitchens. This UCO can be converted to yellow grease through a purification process and then used as an input to biodiesel conversion similar to that of converting vegetable oils from oil seed crops (e.g. canola). From a life cycle perspective, the production of biodiesel from yellow grease originates with the production and use of cooking oils in restaurants; however, UCO from these sources is considered a waste product and no GHG emissions associated with upstream activities are attributed to them, which is consistent with a number of other LCAs of biodiesel from yellow grease (California Environmental Protection Agency, 2009) ((S&T)2 Consultants Inc., 2012) (Chen, et al., 2018) (University of Toronto, 2019). The system boundary for the life cycle carbon intensity of yellow grease biodiesel therefore begins at the restaurant gate, and includes transport of UCO, purification, pre-treatment, biodiesel conversion, distribution, and combustion (Figure 13).

The system boundary for biodiesel from yellow grease is shown in Figure 13. The basic model building blocks for this process include:

- Transport of UCO from restaurants to the processing plant;
- Purification of UCO to produce yellow grease;
- Transport of yellow grease from the processing plant to the biodiesel production plant;
- Pre-treatment of yellow grease;
- Biodiesel production;
- Biodiesel distribution; and
- Biodiesel combustion.

After biodiesel production, the life cycle activities and resulting GHG emissions are assumed to be the same as for crop-based biodiesel pathways. The life cycle inventory and modelling considerations for biodiesel from yellow grease are outlined below.

7.3.2 Modelling and Life Cycle Inventory

Transport of Used Cooking Oil (UCO)

Data for 2017 indicate that all biodiesel produced from yellow grease was produced in Ontario and Québec (Wolinetz, Hein, & Moawad, 2019); however, for the Canadian average template developed for yellow grease biodiesel, it is assumed that UCO is transported by truck from restaurants within the same province as the biodiesel plant over an average distance of 100 km. Users of the Fuel LCA Modelling Tool can modify this transport distance and/or add additional transport modes and distances to align with more specific supply chain configurations in the future.

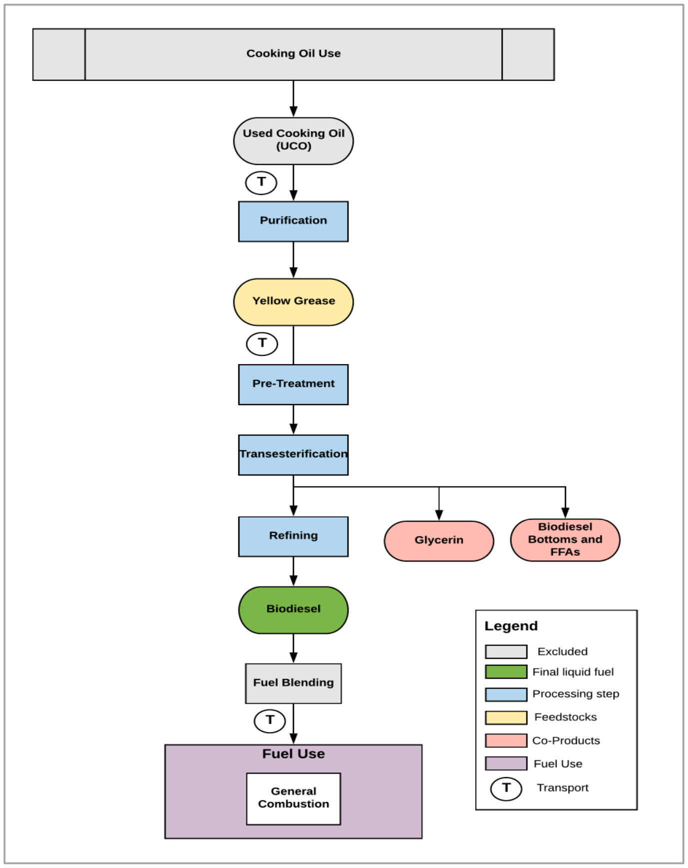

Figure 13. System boundaries for production of biodiesel from yellow grease derived from UCO.

UCO Purification

The mass balance and energy intensity of producing yellow grease by purifying UCO were derived from GHGenius. The data in GHGenius were developed to represent the Canadian context and are used here for the Canadian average pathway ((S&T)2 Consultants Inc., 2012). The mass balance and energy inputs for production of 1 kg of yellow grease from purification of UCO are shown in Table 62.

Table 62. Mass balance and energy inputs for purification of 1 kg of yellow grease from UCO ((S&T)2 Consultants Inc., 2012)

Purification	Amount
Inputs	
UCO (kg)	1.17
Transport of UCO to plant (tkm)*	0.0585
Natural gas (MJ)	0.76
Electricity (kWh)	0.098
Outputs	
Yellow grease (kg)	1
Wastes	
Wastewater (kg)	0.17

**UCO is assumed to be transported 100 km*

Transport of Yellow Grease to Biodiesel Plants

For the Canadian average template developed for yellow grease biodiesel, it is assumed that yellow grease is transported by truck from the processing plants within the same province as the biodiesel plant over an average distance of 100 km. Users of the Fuel LCA Modelling Tool can modify this transport distance and/or add additional transport modes and distances to align with more specific supply chain configurations in the future.

Conversion of Yellow Grease to Biodiesel

As an input to biodiesel conversion, yellow grease has a higher FFA content than oil derived from oil seed crops. As such, a pre-processing step is needed to reduce the FFA content before transesterification (California Environmental Protection Agency, 2009) (University of Toronto, 2019). Data on the energy inputs for pre-processing were obtained from the California-GREET project where an average energy consumption was calculated assuming that UCO is pre-treated using acid esterification and non-acid esterification on an approximately 50/50 basis (California Environmental Protection Agency, 2009). Energy inputs for this pre-treatment step include 0.385 MJ of natural gas per kg of biodiesel produced, and 0.0743 MJ of electricity per kg of biodiesel produced.

After pre-treatment, yellow grease is processed through a biodiesel conversion process similar to that used for other crop-based vegetable oils. A summary of the inputs and outputs of converting yellow grease to biodiesel is provided in Table 5. Unlike conversion of crop-based vegetable oil feedstocks, the conversion process for yellow grease also yields significant amounts of biodiesel distillation bottoms and FFAs, such that the conversion process impacts were allocated between biodiesel, glycerol, distillation bottoms, and FFAs. This allocation was done according to the energy content of the outputs, as per Chen et al. (2018), resulting in 94% of the emissions associated with biodiesel conversion being allocated to the biodiesel.

Table 63. Mass balance and material and energy inputs for production of biodiesel from yellow grease for an average US facility (Chen, et al., 2018).

	Amount (per kg of biodiesel)	Amount (per MJ of biodiesel)
Inputs		
Yellow grease (kg)	1	0.024895
Natural gas (MJ)	1.18	0.029377
Electricity (kWh)	0.0408	0.001017
Biodiesel distillation bottoms (MJ)	0.0005	1.24E-05
Methanol (kg)	0.108	0.0026887
Sulfuric acid (kg)	0.0001	2.49E-06
Hydrochloric acid (kg)	0.0025	6.22E-05
Sodium methylate (kg)	0.0049	0.000122
Sodium hydroxide (kg)	0.0004	9.96E-06
Nitrogen gas (kg)	0.0022	5.48E-05
Outputs		
Glycerol (kg)	0.0905	0.00225
Biodiesel distillation bottoms (kg)	0.003	7.47E-05
Fatty acids (kg)	0.0043	0.000107
Biodiesel (kg)	1	0.0337

**Note – The energy contents of the co-products include (Chen et al. 2018): glycerol - 18.56 MJ/kg; biodiesel distillation bottoms – 39.47 MJ/kg; fatty acids – 39.47 MJ/kg. The energy content of biodiesel is 29.67 MJ/kg.*

Yellow Grease Biodiesel Distribution and Combustion

It is assumed that after conversion of biodiesel from yellow grease that all other life cycle activities related to distribution and combustion are equivalent to those of the crop-based biodiesel pathways modeled in Milestone 3 (see Section 5.3), and that final energy content of the biodiesel is equivalent to conventional biodiesels (29.67 MJ/kg).

7.3.3 Carbon Intensity of Biodiesel from Yellow Grease

The carbon intensity results for biodiesel from yellow grease are summarized in Table 64. The CI for biodiesel from yellow grease is approximately 12 g CO_2 eq./MJ, which is 88% lower than fossil aviation fuel (100 g CO_2 eq./MJ). The primary contributor to the life cycle GHG emissions is biodiesel production, followed by combustion and feedstock production. Feedstock production for biodiesel from yellow grease is notably much lower than that for tallow as the rendering process is less energy intensive and tallow must be heated for transport.

Table 64. Carbon intensity results for biodiesel produced from yellow grease, expressed in g CO_2 eq. per MJ of biodiesel energy.

Life Cycle Stage	Amount	Unit
Feedstock Production	1.9	g CO_2 eq./MJ
Feedstock Transport	0.4	g CO_2 eq./MJ
Pre-Processing of Yellow Grease	0.8	g CO_2 eq./MJ
Biodiesel Production	3.8	g CO_2 eq./MJ
Transport & Distribution	0.8	g CO_2 eq./MJ
Combustion	4.4	g CO_2 eq./MJ
Total	**12**	**g CO_2 eq./MJ**

7.3.4 Uncertainty

Uncertainty analysis was conducted for Canadian average biodiesel from tallow and yellow grease using Monte Carlo analysis. Results of the uncertainty analysis are shown in the violin plots in Section 12 and discussed relative to the uncertainty of other low carbon fuels in that section. Below in Table 65 the key results of the uncertainty analysis for both types of biodiesel are summarized.

Results of the uncertainty analysis show a fairly tight range of possible outcomes at both the high and low end for both fuels. Most of the uncertainty is due to potential variations in energy intensity and yield of the rendering and pre-processing steps for tallow and UCO.

Table 65. Uncertainty analysis results for average Canadian biodiesel from beef tallow and from yellow grease. Results based on Monte Carlo analysis with a confidence interval of 95%.

Final CI	Mean	Median	SD	Min (2.5%)	Max (97.5%)
Biodiesel, from beef tallow, average {CA}					
20.7	20.7	20.4	3.09	15.5	27.6
Biodiesel, from yellow grease, average {CA}					
11.7	11.7	11.6	1.43	9.48	15.0

7.3.5 Data Gaps and Limitations for Waste Biodiesel

The primary limitations for modelling biodiesel production from tallow and yellow grease are a lack of recent, Canadian data on the material and energy inputs to tallow rendering, UCO pretreatment, and biodiesel conversion. Although primary data was available from CEPR for the LCI of ethanol and biodiesel conversion from a number of Canadian producers, there were gaps in this data and challenges with linking specific feedstocks to process which limited its applicability for modelling unique waste biodiesel conversion processes. For rendering and pretreatment, the data used are somewhat dated and also primarily from the U.S., so operating data from Canadian facilities could improve the reliability of the CI calculations for this part of the life cycle. In addition, due to the fossil component of methanol used in conversion, combustion emissions from biodiesel overall appear to be non-negligible despite the exclusion of biogenic carbon, so more representative data on combustion emissions is needed to solidify the modelling.

7.4 Ethanol from MSW

7.4.1 System Boundaries and Descriptions for Yellow Grease Biodiesel

The conversion of MSW to fuels is of increasing interest to low carbon fuel producers. In particular, food waste and yard trimmings that are part of the organics component of MSW can be good feedstocks for fuel because they have high energy content and their properties are very similar to other biomass feedstocks that are commonly used, such as wood biomass and crop-based feedstocks ((Lee, Han, & Wang, 2016).

There are a number of options for converting MSW to ethanol, including Enerkem's conversion of non-recyclable MSW to ethanol, methanol, and other products through gasification[13], and other systems targeted at source-separated organics or organics in the MSW stream; however, there is no data publicly available to model the Enerkem process, and very limited data available to model MSW to ethanol overall. While users of the Fuel LCA Modelling Tool will be able to build their own unique MSW to ethanol pathways, the default pathway provided here is for conversion of yard trimmings from the organic component of MSW to ethanol via fermentation. Yard trimmings generally consist of grass, leaves, and wood and have characteristics similar to other lignocellulosic feedstocks modeled in this study, such as corn stover. As such, they can be converted to cellulosic ethanol via a similar hydrolysis and fermentation process as corn stover and wheat straw.

Since yard trimmings are a waste product, no GHG emissions associated with upstream activities such as production of yard waste or MSW collection systems are attributed to them, which is consistent with assumptions in other LCA studies (Lee, Han, & Wang, 2016) (Kalogo, Habibi, MacLean, & Joshi, 2007). The system boundary for the life cycle carbon intensity of ethanol from MSW therefore begins with the delivery of yard trimmings from a central MSW collection facility to an ethanol plant, and includes pre-treatment, fuel conversion, distribution, and combustion (Figure 13). The unit process building blocks for this process include:

- Transport of yard trimmings to the ethanol plant;

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[13] See Enerkem's process description here: https://enerkem.com/about-us/technology/

- Dilute acid pre-treatment;
- Enzymatic hydrolysis and fermentation;
- Distillation and dehydration;
- Cellulosic ethanol distribution; and
- Cellulosic ethanol combustion.

In reviewing the modelling and results for waste-to-energy systems in the literature and in other modelling tools (e.g. GREET), the system boundary of the assessment often includes consideration of the emissions associated with current waste management practices to determine if there is a net increase or decrease in GHG emissions when redirecting wastes to fuel production. This balance depends heavily on what the current waste management practice is (e.g. landfilling, composting, etc.), projections of market changes if the waste is used for bioenergy, and on the fuel conversion process that is used to convert the waste feedstock into energy. As such, the CI of fuels produced from MSW reported in the literature can vary from jurisdiction to jurisdiction, and from pathway to pathway, and results in the limited amount of literature for converting MSW to ethanol indicate a high level of variability (Kalogo, Habibi, MacLean, & Joshi, 2007).

This approach to modelling the differences between a reference case and the bioenergy case is a form of consequential LCA modelling (market-based recycling model). As discussed in Section 2, the approach for the Fuel LCA Modelling Tool is to use a cut-off approach for the recycling or reuse of materials beyond the first life of the material. As such, any GHG emissions credit or burden associated with the redirection of these wastes to bioenergy production are not included within the boundary when calculating the CI of converting MSW to ethanol (the second life of the material).

7.4.2 Modelling and Life Cycle Inventory

Transport of Yard Trimmings

Yard trimmings collected within the MSW management system are assumed to be transported from a centralized MSW depot to an ethanol producer using an average diesel truck (as modelled in Milestone 2). The moisture content of the yard trimmings is assumed to be 60% (Lee, Han, & Wang, 2016), and the dry mass and mass of the moisture are accounted for in calculating the emissions from feedstock transport. As per the corn stover cellulosic ethanol conversion process, 0.143 kg (dry mass) of feedstock are required to yield 1 MJ of fuel (HHV), and at 60% moisture content this requires that 0.229 kg of feedstock be transported to the facility for every MJ of cellulosic ethanol produced. Since there are no current data available on existing supply chains for producers of MSW from ethanol in Canada, the feedstock transport distance is assumed to be 100 km, and requiring 0.0229 tkm per MJ of cellulosic ethanol. Users of the Fuel LCA Modelling Tool can modify this transport distance and/or add additional transport modes and distances to align with more specific supply chain configurations in the future. Users can also update the transport calculations to reflect alternative moisture content data in the future.

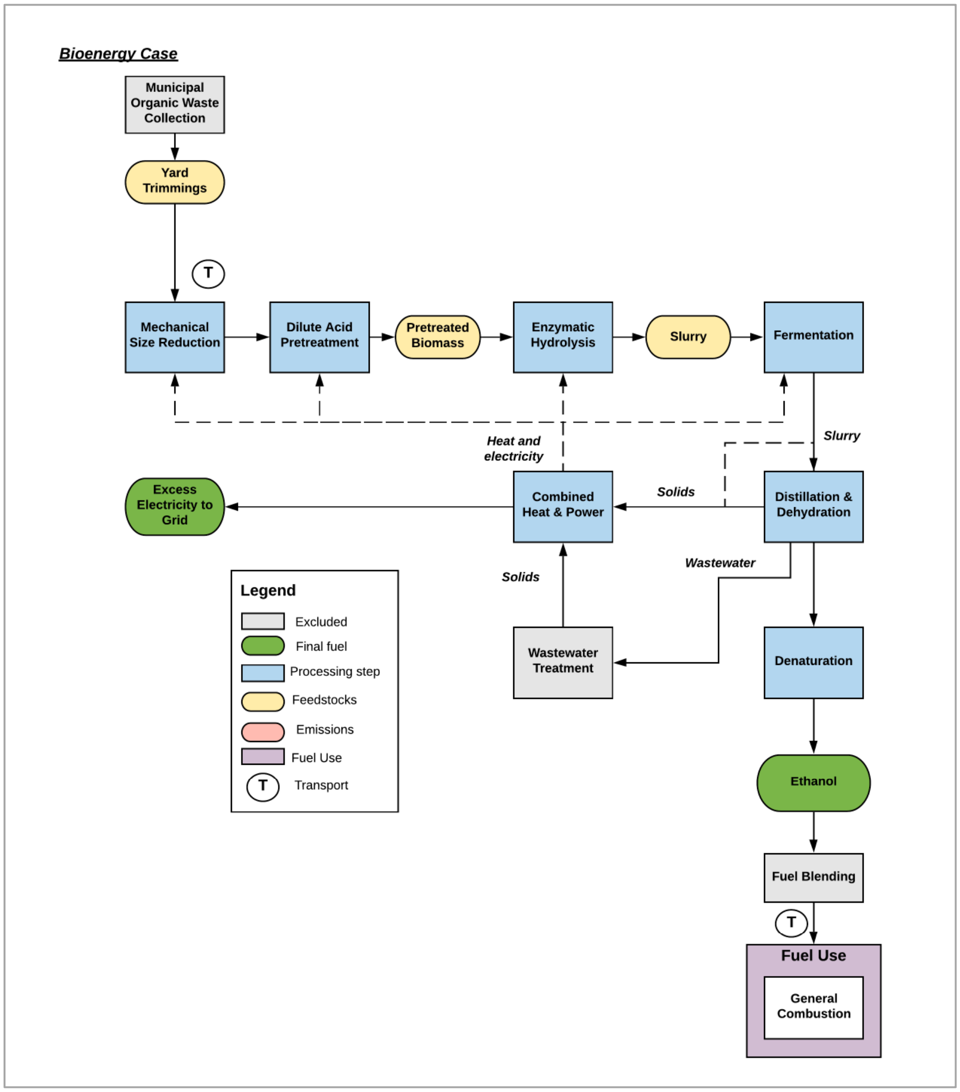

Figure 14. System boundaries for production of ethanol from yard trimmings derived from MSW.

Pretreatment and Conversion to Ethanol

The pretreatment and conversion of yard trimmings to ethanol was assumed to be done via the same cellulosic ethanol process that was modelled for conversion of corn stover to cellulosic ethanol. A similar assumption was made in modelling the conversion of yard trimmings to ethanol in the GREET tool (Lee, Han, & Wang, 2016). This conversion process includes mechanical size reduction, dilute acid pretreatment, and fuel conversion via hydrolysis and fermentation (see Section 6.2). As a result of the high moisture content of the feedstock relative to corn stover, more energy is required to dry the feedstock and so the conversion of yard trimmings to ethanol does not result in a surplus of electricity that could be sold to the grid. As such, unlike the conversion of corn stover for which surplus electricity is produced (see Section 6.2), there are no GHG emissions credits generated for conversion of yard trimmings. The additional energy needed to dry the incoming feedstock is estimated to be 0.61 mmBtu (~644 MJ) of natural gas per dry tonne of feedstock, as calculated in Lee et al. for an average US process (Lee, Han, & Wang, 2016). The cellulosic ethanol conversion process requires 0.143 kg (dry) of yard trimmings, such that an additional 0.092 MJ of natural gas is required per MJ of fuel produced.

MSW-Based Ethanol Distribution and Combustion

Since there are no established production and distribution supply chains for ethanol produced from MSW in Canada, it was assumed that fuel distribution to end users and fuel combustion would be equivalent to distribution and combustion of the crop-based bioethanol pathways modelled in Section 5. Cellulosic ethanol from yard trimmings was also assumed to have the same HHV as crop-based bioethanol.

7.4.3 Carbon Intensity of Ethanol from Yard Trimmings

The carbon intensity results for cellulosic ethanol from MSW yard trimmings are summarized in Table 66. For this average default pathway the CI is estimated to be approximately 30 g of CO_2 eq. per MJ of fuel (HHV) for neat/unblended fuel, which is approximately 67% lower than the CI estimated for conventional gasoline (92 g CO_2 eq./MJ). The primary contributor to the life cycle GHG emissions of the pathway is the conversion of the feedstock into cellulosic ethanol via hydrolysis and fermentation, accounting for 80% of life cycle GHG emissions. The key difference in CI between cellulosic ethanol from MSW and conventional gasoline is the combustion emissions. While gasoline combustion emissions are approximately 66 g CO_2 eq. per MJ, combustion emissions from waste-based cellulosic ethanol are nearly zero due to the biogenic nature of the carbon contained in the fuel.

Table 66. Carbon intensity results for cellulosic ethanol produced from yard trimmings from MSW, expressed in g CO_2 eq. per MJ of ethanol (HHV).

Life Cycle Stage	Amount	Unit
Feedstock Transport	3.0	g CO_2 eq./MJ
Pretreatment	2.0	g CO_2 eq./MJ
Hydrolysis and fermentation	24	g CO_2 eq./MJ
Transport & Distribution	0.8	g CO_2 eq./MJ
Combustion	0.4	g CO_2 eq./MJ
Total	**30**	**g CO_2 eq./MJ**

Uncertainty analysis was conducted for ethanol from MSW yard trimmings based on data quality and fit for purpose evaluations of the LCI data. Results of the Monte Carlo analysis indicate that the CI could vary significantly depending on the data and assumptions used, ranging from 76% higher than the default value, to 45% lower. The uncertainty of the results for ethanol from MSW is also shown in the violin plots in Section 12 of the report, including a comparison with the baseline CI value for conventional gasoline and for other bioethanol and cellulosic ethanol pathways.

Table 67. Uncertainty analysis results for average Canadian cellulosic ethanol from yard trimmings collected in MSW. Results based on Monte Carlo analysis with a confidence interval of 95%.

Final CI	Mean	Median	SD	Min (2.5%)	Max (97.5%)
Ethanol, from yard trimmings, average {CA}					
30.0	30.1	28.6	9.2	16.4	52.7

7.4.4 Data Gaps and Limitations for Ethanol from MSW

Since there are no data and very few existing MSW-to-ethanol producers in Canada, all of the LCI data used are based on previous studies from regions outside of Canada which were modified using assumptions and guidance from the literature. As such, the primary limitations for modelling cellulosic ethanol production from MSW is a lack of recent Canadian data on the material and energy inputs to the conversion process, and specific data on the feedstock(s) that would be used. For the purposes of building a default pathway for the Fuel LCA Modelling Tool, we have modelled the conversion of yard trimmings using a cellulosic ethanol conversion process; however, other feedstocks from MSW could be used, and other conversion processes could be used (e.g. gasification), which could change the CI substantially. As such, the CI results are generally limited to this specific pathway, and the uncertainty ranges provided should be used as upper and lower ranges of possible outcomes depending on variations in the technology and feedstock characteristics.

8. Renewable Natural Gas (RNG)

Renewable natural gas (RNG) is methane gas derived from organic materials and waste streams that has been produced and had impurities removed to a level that meets current natural gas pipeline specifications or vehicle fuel standards (Canadian Gas Association, 2014). RNG can typically be produced from anaerobic digestion or gasification of agriculture or agri-food residues (crop residues, livestock manure, food waste), forestry by-products (e.g. harvest residues), and MSW streams and WWT sludge. The biogas from these processes must then be upgraded to RNG by removing impurities to reach an appropriate methane concentration. RNG is considered a renewable energy feedstock due to the biogenic nature of the source, and the carbon released when RNG is combusted is biogenic in nature and therefore not counted as an increase in atmospheric carbon under the current national GHG inventory generation and reporting methods used in Canada.

In a 2019 study conducted for Natural Resources Canada, it was identified that there are currently 12 operational RNG production facilities in Canada, with two others expected to begin operation within the next 2 years (CIRAIG, 2019). These 14 facilities include:

- 2 facilities converting WWT sludge;
- 1 facility converting household organic wastes;
- 4 facilities converting organic wastes;
- 3 facilities converting dairy manure and off-farm wastes; and
- 4 facilities upgrading landfill gas.

Determining the CI of RNG systems is challenging due to a lack of primary data from the small number of current producers, and due to the potential variability in CI that could result from the use of the many different feedstocks available, and use of different forms of anaerobic digestion and upgrading technologies. A survey of current producers was conducted in the summer of 2019 and resulted in collection of some operating data from a small subset of 5 of the currently active producers (CIRAIG, 2019); however, these data were incomplete and were combined with literature data to produce average inventories for anaerobic digestion and biogas upgrading which are not specific to any given feedstock or technology.

For the purposes of the Fuel LCA Modelling Tool, we have established the basic model building blocks for 4 RNG pathways, including capture and upgrading of landfill gas, as well as anaerobic digestion and upgrading of biogas from 3 sources of organic materials, including WWT sludge, organics from MSW, and livestock manure. The lack of available data from Canadian producers limited the ability to develop high-resolution models of these four pathways, but instead allowed for the development of more generic building blocks for basic unit processes such as anaerobic digestion and biogas upgrading. It is expected that users of the Fuel LCA Modelling tool will use and expand upon these basic building blocks in the future to develop more specific pathways.

The following sections provide an overview of the system boundaries, modelling, and CI results for each of the 4 RNG pathways.

8.1 RNG from Landfill Gas

8.1.1 System Boundaries and Descriptions for RNG from Landfill Gas

Landfill gas is biogas generated from the decomposition of organic materials in municipal landfills. It is composed primarily of methane, but also contains carbon dioxide and several other substances in small amounts (e.g. hydrogen sulfide). Conventional practice is to flare landfill gas to convert most of the methane to carbon dioxide in order to reduce GHG emissions, and to reduce other criteria air pollutants (Mintz, Han, Wang, & Saricks, 2010). While landfills in some jurisdictions may also include energy generation from the capture of landfill gas, this is not the case in all instances and unused landfill gas represents a potential feedstock for RNG that is widely available.

Since landfill gas is a waste product originating from the organic fraction of MSW, no GHG emissions associated with upstream activities such as production of MSW or MSW collection systems are attributed to it, which is consistent with assumptions used in the GREET LCA model (Lee, Han, & Wang, 2016). In addition, it is assumed that the landfills from which landfill gas is obtained are already capturing this biogas for the purposes of flaring it to reduce methane emissions. As such, the energy use and emissions associated with capturing landfill gas using a blower system are also excluded from the system boundary since this would occur regardless of whether the biogas is directed to RNG production or not.

The system boundary for the life cycle carbon intensity of RNG from landfill gas therefore begins with the upgrading of captured landfill gas (Figure 15). The unit process building blocks for this process include:

- Upgrading of landfill biogas to RNG;
- Distribution and storage in the natural gas system; and
- Combustion.

In reviewing the modelling and results for waste-to-energy systems in the literature and in other modelling tools (e.g. GREET), the system boundary of the assessment often includes consideration of the emissions associated with current waste management practices to determine if there is a net increase or decrease in GHG emissions when redirecting wastes to fuel production. This balance depends heavily on what the current waste management practice is (e.g. landfilling, composting, etc.), projections of market changes if the waste is used for bioenergy, and on the fuel conversion process that is used to convert the waste feedstock into energy. As such, the CI of fuels produced from MSW reported in the literature can vary from jurisdiction to jurisdiction, and from pathway to pathway, and results in the limited amount of literature for converting MSW to ethanol indicate a high level of variability (Kalogo, Habibi, MacLean, & Joshi, 2007).

This approach to modelling the differences between a reference case and the bioenergy case is a form of consequential LCA modelling (market-based recycling model). As discussed in Section 2, the approach for the Fuel LCA Modelling Tool is to use a cut-off approach for the recycling or reuse of materials beyond the first life of the material. As such, any GHG emissions credit or burden associated with the redirection of these wastes to bioenergy production are not included within the boundary when calculating the CI of converting MSW to ethanol (the second life of the material).

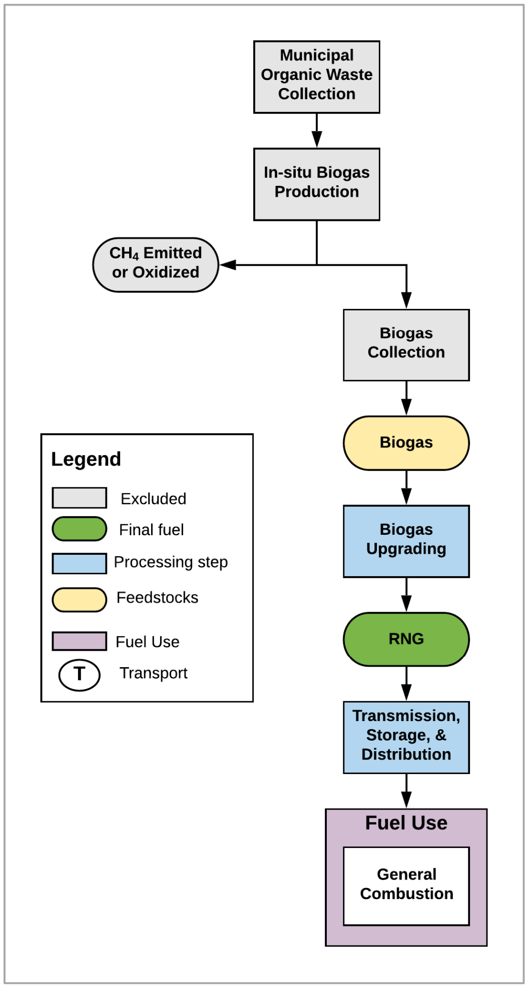

Figure 15. System boundaries for production of RNG from landfill gas.

8.1.2 Modelling and Life Cycle Inventory

Biogas Upgrading

The LCI for biogas upgrading is based on a combination of primary data from a limited number of Canadian RNG producers and secondary data from the literature used to fill data gaps in the primary data set. These confidential data were compiled by CIRAIG and shared with ECCC via NRCan for use in the Fuel LCA Modelling tool (CIRAIG, 2019). The life cycle GHG emissions associated with upgrading of landfill gas to RNG are based on energy consumption to power the process and direct process emissions of methane and carbon dioxide. These direct emissions are a function of the incoming biogas composition, and an average biogas composition profile was used from the literature since no specific Canadian data were available (CIRAIG, 2019). A summary of the inputs and outputs and biogas composition is provided in Table 68.

Table 68. Inputs, outputs, biogas composition, and RNG composition for upgrading of landfill gas to RNG in an average Canadian facility (CIRAIG, 2019).

	Amount (per 1 m3 of RNG)	Amount (per MJ of RNG)*
Inputs		
Biogas (m^3)	3.95	0.104
Electricity (kWh)	0.862	0.023
Activated carbon (kg)	0.001	2.63E-05
Outputs		
RNG (m^3)	1	0.026
Methane (kg)**	0.00163	4.29E-05
Carbon dioxide (kg)***	3.43	0.09
Landfill Gas Composition		
Methane, biogenic (%vol)	45	
Hydrogen (%vol)	0	
Cardon dioxide, biogenic (%vol)	40	
Nitrogen (%vol)	15	
Oxygen (%vol)	1	
Hydrogen sulfide (%vol)	0.0001	
Ammonia (%vol)	0.000005	
RNG Composition		
Methane, biogenic (%vol)	97.46	
Hydrogen (%vol)	0	
Carbon dioxide, biogenic (%vol)	0.78	
Nitrogen (%vol)	1.735	
Oxygen (%vol)	0.02	
Hydrogen sulfide (%vol)	0	
Ammonia (%vol)	0	

**Note – The energy content of RNG is 38 MJ/m3* (CIRAIG, 2019).

***Note – Methane emissions are assumed to be flared. Methane emissions would be higher in cases where emissions are only vented*

****Note – Carbon dioxide emissions from biogas upgrading are biogenic in nature and therefore excluded from CI calculations.*

Calculations of the methane and carbon dioxide emissions from the biogas upgrading process are summarized in the calculation sheets provided for RNG in the supporting material. Methane emissions from biogas upgrading were assumed to be flared at an efficiency of 99.5% therefore reducing methane emissions significantly. In instances where methane is not flared, the CI would be significantly higher. Activated carbon was excluded from the CI calculations for upgrading biogas due to the insignificant amount used and its low contribution to the life cycle CI. The composition of the RNG produced from this process is assumed to be the same regardless of the input biogas.

RNG Distribution and Combustion

Since there are no data available on established Canadian production and distribution supply chains for RNG, it was assumed that fuel distribution to end users would be equivalent to distribution of conventional natural gas modelled in Milestone 2 (EarthShift Global, WSP, Introspective Systems, 2019b). This is a reasonable assumption since it is expected that RNG would replace conventional natural gas in current distribution and use infrastructure.

Primary data were not available on the combustion emissions from RNG. Since the carbon contained in the fuel is biogenic, it is excluded from the CI calculations. Estimates of methane and nitrous oxide emissions associated with combustion of RNG were obtained from a summary of emissions factors for the British Columbia renewable fuels regulation (British Columbia Ministry of Environment and Climate Change Strategy, 2017). It is noted that methane and nitrous oxide emissions could vary depending on the efficiency of combustion, which is not reflected in this average case.

8.1.3 Carbon Intensity of RNG from Landfill Gas

The carbon intensity results for RNG produced from landfill gas are summarized in Table 69. For this average default pathway, the CI is estimated to be approximately 6.0 g of CO_2 eq. per MJ of fuel (HHV), which is approximately 91% lower than the CI estimated for conventional natural gas (67 g CO_2 eq./MJ). The primary contributor to the life cycle GHG emissions of the pathway is the upgrading of biogas, accounting for 88% of life cycle GHG emissions. The key difference in CI between RNG and conventional natural gas is the combustion emissions. While natural gas combustion emissions are approximately 53 g CO_2 eq. per MJ, combustion emissions from RNG are nearly zero due to the biogenic nature of the carbon contained in the fuel.

Table 69. Carbon intensity results for RNG produced from landfill gas, expressed in g CO_2 eq. per MJ of RNG (HHV).

Life Cycle Stage	Amount	Unit
Biogas upgrading	5.3	g CO_2 eq./MJ
Transport & Distribution	0.6	g CO_2 eq./MJ
Combustion	0.3	g CO_2 eq./MJ
Total	**6.0**	**g CO_2 eq./MJ**

Results of the uncertainty analysis for RNG produced from landfill gas are provided in Section 12.

8.2 RNG from WWT Sludge

8.2.1 System Boundaries and Descriptions for RNG from WWT Sludge

Biogas can also be generated from the anaerobic digestion of WWT sludge. WWT sludge is a by-product of municipal sewage treatment processes. Because the sludge is fairly homogenous and has a high energy content, it is a good potential feedstock for biofuels. Conventional practice is to process WWT sludge with an anaerobic digestion process which yields biogas and digestate. The biogas is typically flared to reduce methane emissions, and the digestate is used a soil amendment in agricultural fields (Lee U. , Han, Demirtas, Wang, & Tao, 2016). A survey of Canadian RNG producers in 2019 indicated two facilities that are expected to produce RNG from WWT sludge within the next two years, but otherwise no other recorded activity for this pathway.

Since the sludge is a waste product originating from WWT plants, no GHG emissions associated with upstream activities such as production of wastewater or collection and treatment of wastewater are attributed to it, which is consistent with assumptions used in the GREET LCA model (Lee U. , Han, Demirtas, Wang, & Tao, 2016).

The system boundary for the life cycle carbon intensity of RNG from WWT sludge therefore begins with the transport of sludge to an RNG facility (Figure 16). The unit process building blocks for this process include:

- Transport of WWT sludge to an RNG facility;
- Anaerobic digestion of the WWT sludge to produce biogas and digestate;
- Upgrading of biogas to RNG;
- Distribution and storage in the natural gas system; and
- Combustion.

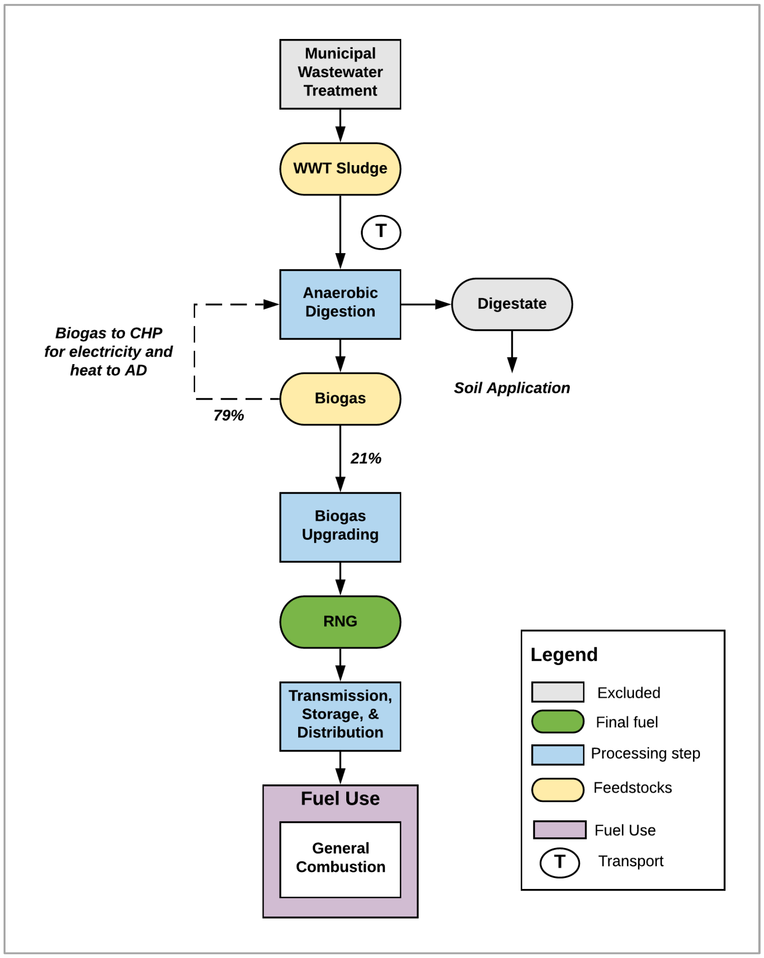

Figure 16. System boundaries for production of RNG from WWT sludge.

8.2.2 Modelling and Life Cycle Inventory

Transport of WWT Sludge

WWT sludge collection from WWT plants is assumed to be transported to an RNG producer using an average diesel truck (as modelled in Milestone 2). The moisture content of the WWT sludge is assumed to be 90% (Lee U. , Han, Demirtas, Wang, & Tao, 2016), and the dry mass and mass of the moisture are accounted for in calculating the emissions from feedstock transport. Based on data compiled by CIRAIG, it requires 1.196 kg (dry mass) of feedstock to yield 1 m^3 of biogas from anaerobic digestion. At 90% moisture content this requires that 2.27 kg of wet sludge be transported to the facility for every m^3 of biogas produced. Since there are no current data available on existing supply chains for producers of RNG from WWT sludge in Canada, the feedstock transport distance is assumed to be 50 km. Users of the Fuel LCA Modelling Tool can modify this transport distance and/or add additional transport modes and distances to align with more specific supply chain configurations in the future. Users can also update the transport calculations to reflect alternative moisture content data in the future.

Anaerobic Digestion

The anaerobic digestion of organic material was modeled from a combination of primary and secondary data compiled to develop an average Canadian anaerobic digestion process (CIRAIG, 2019). The average process modeled is based on an anaerobic digestion process that includes an onsite CHP plant which provides heat and electricity to the process. It is assumed that the CHP accounts for all the required energy of the process with the exception of a small amount of natural gas heat and grid electricity. The process yields biogas and digestate. A significant portion of the biogas produced is used to power the CHP unit, while the rest is directed to RNG production. The digestate is assumed to be stored in a closed location for potential future use as a soil amendment. The inputs and outputs of the average anaerobic digestion process are summarized in Table 73 below. The GHG emissions associated with production of biogas by anaerobic digestion were allocated between the biogas output and the digestate based on their energy content, resulting in 18.3% of the GHG emissions being allocated to biogas. With respect to the input of organic material to the process, the data compiled by CIRAIG were for an average process using a mixture of feedstocks; however, in order to model RNG pathways from individual organic feedstocks, it was assumed that the same total mass of organic material input would be required regardless of the feedstock used. This is a simplifying assumption because the incoming organics would have different moisture contents and properties; however, specific anaerobic digestion data were not available for each type of feedstock.

Table 70. Inputs and outputs for anaerobic digestion of organic material to produce biogas for RNG upgrading in an average Canadian facility (CIRAIG, 2019).

	Amount (per 1 m3 of biogas processed)
Inputs	
Organic material (kg)*	1.196
Sodium hydroxide (kg)	2.18E-05
Electricity, from grid (kWh)	0.145
Heat – from internal CHP (MJ)	4.65
Heat – from natural gas (MJ)	0.002
Outputs	
Biogas – to be upgraded to RNG (m^3)**	0.2086
Biogas – for use in CHP (m^3)**	0.7914
Heat – from CHP (MJ)	4.854
Electricity – from CHP (kWh)	2.127
Digestate (kg)***	8.581
Methane – from CHP (kg)	7.63E-05
Nitrous oxide – from CHP (kg)	2.81E-07
Methane – from digester (kg)	0.00307

**Note – Data collected by CIRAIG for the amount of organic material input was based on an average mix of different organic materials, including food waste, WWT sludge, used cooking oil, pig slurry, and cow slurry. In order to model a specific pathway (e.g. WWT sludge) a simplifying assumption was used that the total of these different inputs is the required mass of organic inputs of any type.*

***Note – The energy content of the biogas produced is 25 MJ/m3* (CIRAIG, 2019).

****Note – The energy content of the digestate is assumed to be 13 MJ/kg* (Durdevic, Blecich, & Lenic, 2018)

Upgrading of Biogas to RNG

The LCI for biogas upgrading is based on a combination of primary data from a limited number of Canadian RNG producers and secondary data from the literature used to fill data gaps in the primary data set. These confidential data were compiled by CIRAIG and shared with ECCC via NRCan for use in the Fuel LCA Modelling tool (CIRAIG, 2019). The life cycle GHG emissions associated with upgrading of biogas from anaerobic digestion to RNG are based on energy consumption to power the process and direct process emissions of methane and carbon dioxide. These direct emissions are a function of the incoming biogas composition, and an average biogas composition from anaerobic digestion was used from the literature since no specific Canadian data were available (CIRAIG, 2019). A summary of the inputs and outputs and biogas composition is provided in Table 71.

Table 71. Inputs, outputs, biogas composition, and RNG composition for upgrading of biogas from anaerobic digestion to RNG in an average Canadian facility (CIRAIG, 2019).

	Amount (per 1 m3 of RNG)	Amount (per MJ of RNG)*
Inputs		
Biogas (m^3)	3.95	0.104
Electricity (kWh)	0.862	0.023
Activated carbon (kg)	0.001	2.63E-05
Outputs		
RNG (m^3)	1	0.026
Methane (kg)**	0.0054	0.00014
Carbon dioxide (kg)***	2.53	0.067
Landfill Gas Composition		
Methane, biogenic (%vol)	65	
Hydrogen (%vol)	0	
Cardon dioxide, biogenic (%vol)	35	
Nitrogen (%vol)	0.2	
Oxygen (%vol)	0	
Hydrogen sulfide (%vol)	0.0005	
Ammonia (%vol)	0.0001	
RNG Composition		
Methane, biogenic (%vol)	97.46	
Hydrogen (%vol)	0	
Carbon dioxide, biogenic (%vol)	0.78	
Nitrogen (%vol)	1.735	
Oxygen (%vol)	0.02	
Hydrogen sulfide (%vol)	0	
Ammonia (%vol)	0	

**Note – The energy content of RNG is 38 MJ/m3* (CIRAIG, 2019).

***Note – Methane emissions are assumed to be flared. Methane emissions would be higher in cases where emissions are only vented*

****Note – Carbon dioxide emissions from biogas upgrading are biogenic in nature and therefore excluded from CI calculations.*

Calculations of the methane and carbon dioxide emissions from the biogas upgrading process are summarized in the calculation sheets provided for RNG in the supporting material. Methane emissions from biogas upgrading were assumed to be flared at an efficiency of 99.5% therefore reducing methane emissions significantly. In instances where methane is not flared, the CI would be significantly higher. Activated carbon was excluded from the CI calculations for upgrading biogas due to the insignificant amount used and its low contribution to the life cycle CI. The composition of the RNG produced from this process is assumed to be the same regardless of the input biogas.

RNG Distribution and Combustion

Since there are no data available on established Canadian production and distribution supply chains for RNG, it was assumed that fuel distribution to end users would be equivalent to distribution of conventional natural gas modelled in Milestone 2 (EarthShift Global, WSP, Introspective Systems, 2019b). This is a reasonable assumption since it is expected that RNG would replace conventional natural gas in current distribution and use infrastructure.

Primary data were not available on the combustion emissions from RNG. Since the carbon contained in the fuel is biogenic, it is excluded from the CI calculations. Estimates of methane and nitrous oxide emissions associated with combustion of RNG were obtained from a summary of emissions factors for the British Columbia renewable fuels regulation (British Columbia Ministry of Environment and Climate Change Strategy, 2017). It is noted that methane and nitrous oxide emissions could vary depending on the efficiency of combustion, which is not reflected in this average case.

8.2.3 Carbon Intensity of RNG from WWT Sludge

The carbon intensity results for RNG produced from anaerobic digestion and upgrading of WWT sludge are summarized in Table 72. For this average default pathway, the CI is estimated to be approximately 26 g of CO_2 eq. per MJ of fuel (HHV), which is approximately 61% lower than the CI estimated for conventional natural gas (67 g CO_2 eq./MJ). The primary contributor to the life cycle GHG emissions of the pathway is the anaerobic digestion of the WWT sludge, accounting for 38% of life cycle GHG emissions. The CI of biogas upgrading is noted to be higher than upgrading of landfill gas because the incoming biogas is assumed to have a higher methane content and thus emissions of unflared methane are higher. Feedstock transport also makes a significant contribution to total life cycle GHG emissions, accounting for 28% of emissions. This is because the WWT sludge has a very high moisture content when transported to the RNG facility. In an alternative scenario the WWT sludge may be dewatered prior to transport and this would require additional energy; however, these data were not available.

Table 72. Carbon intensity results for RNG produced from WWT sludge, expressed in g CO_2 eq. per MJ of RNG (HHV).

Life Cycle Stage	Amount	Unit
Feedstock transport to RNG facility	7.4	g CO_2 eq./MJ
Anaerobic digestion	10	g CO_2 eq./MJ
Biogas upgrading	8.1	g CO_2 eq./MJ
Transport & Distribution	0.6	g CO_2 eq./MJ
Combustion	0.3	g CO_2 eq./MJ
Total	**26**	**g CO_2 eq./MJ**

Results of the uncertainty analysis for RNG produced from WWT sludge are provided later in this section, and also in the violin plots in Section 12.

8.3 RNG from MSW Organics

8.3.1 System Boundaries and Descriptions for RNG from MSW Organics

Biogas can also be generated from the anaerobic digestion of organic materials found in MSW (e.g. food scraps). Organics, including yard trimmings and food scraps, constitute approximately 40% of the MSW stream in most Canadian municipalities (Environment Canada, 2013). Management of organics in MSW ranges from various forms of composting to anaerobic digestion systems, and a portion of organic household waste also ends up on the main solid waste stream that is sent to landfills. A survey of Canadian RNG producers in 2019 indicated that five facilities are currently producing RNG from organic waste streams.

Since the organics are a waste product, no GHG emissions associated with upstream activities such as production of the materials or collection and treatment of the materials are attributed to them. The system boundary for the life cycle carbon intensity of RNG from MSW organics therefore begins with the transport of organics from a central MSW collection point to an RNG facility (Figure 17). The unit process building blocks for this process include:

- Transport of organics to an RNG facility;
- Anaerobic digestion of the organics to produce biogas and digestate;
- Upgrading of biogas to RNG;
- Distribution and storage in the natural gas system; and
- Combustion.

8.3.2 Modelling and Life Cycle Inventory

Transport of Organics

Organics collected in MSW systems are assumed to be transported to an RNG producer using an average diesel truck (as modelled in Milestone 2). The moisture content of the organics is assumed to be 70% (Lee U. , Han, Demirtas, Wang, & Tao, 2016), and the dry mass and mass of the moisture are accounted for in calculating the emissions from feedstock transport. Based on data compiled by CIRAIG, it requires 1.196 kg (dry mass) of feedstock to yield 1 m^3 of biogas from anaerobic digestion. At 70% moisture content this requires that 2.03 kg of wet organics be transported to the facility for every m^3 of biogas produced. Since there are no current data available on existing supply chains for producers of RNG from MSW organics in Canada, the feedstock transport distance is assumed to be 50 km. Users of the Fuel LCA Modelling Tool can modify this transport distance and/or add additional transport modes and distances to align with more specific supply chain configurations in the future. Users can also update the transport calculations to reflect alternative moisture content data in the future.

Anaerobic Digestion

The anaerobic digestion process to convert organics from MSW to biogas for RNG production was assumed to be the same as the process for WWT sludge. This is a simplifying assumption that was required due to the low-resolution inventory data available from the CIRAIG study which did not allow for the characterization of unique anaerobic digestion processes specific to the incoming feedstock type. A summary of the average Canadian anaerobic digestion process is provided in the previous section.

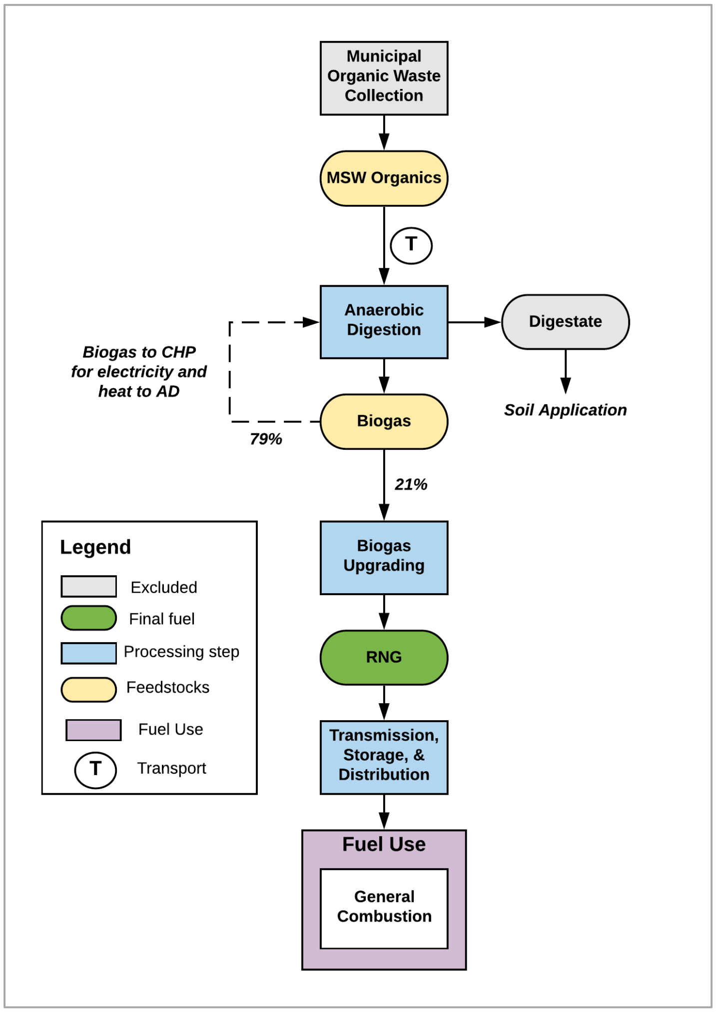

Figure 17. System boundaries for production of RNG from MSW organics.

Upgrading of Biogas to RNG

The upgrading process for biogas from anaerobic digestion of organics from MSW was assumed to be the same as that for WWT sludge and is based on an average Canadian process developed from a limited sample of Canadian producers and supplemented with literature data (CIRAIG, 2019). A summary of this process is provided in the previous section.

RNG Distribution and Combustion

Since there are no data available on established Canadian production and distribution supply chains for RNG, it was assumed that fuel distribution to end users would be equivalent to distribution of conventional natural gas modelled in Milestone 2 (EarthShift Global, WSP, Introspective Systems, 2019b). This is a reasonable assumption since it is expected that RNG would replace conventional natural gas in current distribution and use infrastructure.

Primary data were not available on the combustion emissions from RNG. Since the carbon contained in the fuel is biogenic, it is excluded from the CI calculations. Estimates of methane and nitrous oxide emissions associated with combustion of RNG were obtained from a summary of emissions factors for the British Columbia renewable fuels regulation (British Columbia Ministry of Environment and Climate Change Strategy, 2017). It is noted that methane and nitrous oxide emissions could vary depending on the efficiency of combustion, which is not reflected in this average case.

8.3.3 Carbon Intensity of RNG from MSW Organics

The carbon intensity results for RNG produced from anaerobic digestion and upgrading of MSW organics are summarized in Table 73. For this average default pathway, the CI is estimated to be approximately 26 g of CO_2 eq. per MJ of fuel (HHV), which is approximately 61% lower than the CI estimated for conventional natural gas (67 g CO_2 eq./MJ). The primary contributor to the life cycle GHG emissions of the pathway is the anaerobic digestion of the organics, accounting for 38% of life cycle GHG emissions. The CI of biogas upgrading is noted to be higher than upgrading of landfill gas because the incoming biogas is assumed to have a higher methane content and thus emissions of unflared methane are higher. Feedstock transport also makes a significant contribution to total life cycle GHG emissions, accounting for 25% of emissions. This is because the organics have a high moisture content when transported to the RNG facility.

Table 73. Carbon intensity results for RNG produced from MSW organics, expressed in g CO_2 eq. per MJ of RNG (HHV).

Life Cycle Stage	Amount	Unit
Feedstock transport to RNG facility	6.6	g CO_2 eq./MJ
Anaerobic digestion	10	g CO_2 eq./MJ
Biogas upgrading	8.1	g CO_2 eq./MJ
Transport & Distribution	0.6	g CO_2 eq./MJ
Combustion	0.3	g CO_2 eq./MJ
Total	**26**	**g CO_2 eq./MJ**

Results of the uncertainty analysis for RNG produced from MSW organics are provided later in this section and also in the violin plots in Section 12.

8.4 RNG from Livestock Manure

8.4.1 System Boundaries and Descriptions for RNG from Livestock Manure

Biogas can also be generated from the anaerobic digestion of livestock manure. Livestock manure contains high concentrations of nutrients that are useful for enhancing soil health and fertility. As such, conventional practice for livestock manure management on Canadian farms is to store the manure and apply it to agricultural fields as a soil amendment, with over 3.4 million hectares of land receiving animal manure as an amendment each year (Beef Cattle Research Council, 2016). The type of storage, length of storage, and the rate of seasonal application of manure will vary depending on the location and type of livestock operation (Beaulieu, 2004). As an alternative to storage and direct soil application through which much of biogas is lost, low carbon fuel producers can process livestock manure and convert it to RNG through a process of anaerobic digestion and upgrading. Through the anaerobic digestion process, the biogas produced can be captured and used for energy as well as directed to RNG upgrading, and the digestate produced from anaerobic digestion can be used as a soil amendment. This potential to capture and use the biogas as an alternative to fossil fuels has brought interest to this feedstock, although a survey of Canadian RNG producers in 2019 indicated only two facilities are currently producing RNG from livestock manure, with a third expected to begin operation within the next two years.

Since the manure is a waste product originating from livestock rearing, no GHG emissions associated with upstream activities such as feeding and rearing livestock or collection of manure on the farm are attributed to it, which is consistent with assumptions used in the GREET LCA model (Lee U. , Han, Demirtas, Wang, & Tao, 2016).

The system boundary for the life cycle carbon intensity of RNG from livestock manure therefore begins with the transport of manure to an RNG facility (Figure 18). The unit process building blocks for this process include:

- Transport of manure to an RNG facility;
- Anaerobic digestion of the manure to produce biogas and digestate;
- Upgrading of biogas to RNG;
- Distribution and storage in the natural gas system; and
- Combustion.

8.4.2 Modelling and Life Cycle Inventory

Transport of Organics

Livestock manure produced from Canadian farms is assumed to be transported to an RNG producer using an average diesel truck (as modelled in Milestone 2). The moisture content of the manure is assumed to be 88% (Lee U. , Han, Demirtas, Wang, & Tao, 2016), and the dry mass and mass of the moisture are accounted for in calculating the emissions from feedstock transport. Based on data compiled by CIRAIG, it requires 1.196 kg (dry mass) of feedstock to yield 1 m^3 of biogas from anaerobic digestion. At 88% moisture content this requires that 2.25 kg of wet manure be transported to the facility for every m^3 of biogas produced. Since there are no current data available on existing supply chains for producers of RNG from manure in Canada, the feedstock transport distance is assumed to be 50 km. Users of the Fuel LCA Modelling Tool can modify this transport distance and/or add additional transport modes and distances to align with more specific supply chain configurations in the future. Users can also update the transport calculations to reflect alternative moisture content data in the future.

Anaerobic Digestion

The anaerobic digestion process to convert livestock manure to biogas for RNG production was assumed to be the same as the process for WWT sludge. This is a simplifying assumption that was required due to the low-resolution inventory data available from the CIRAIG study which did not allow for the characterization of unique anaerobic digestion processes specific to the incoming feedstock type. A summary of the average Canadian anaerobic digestion process is provided in Section 8.2.

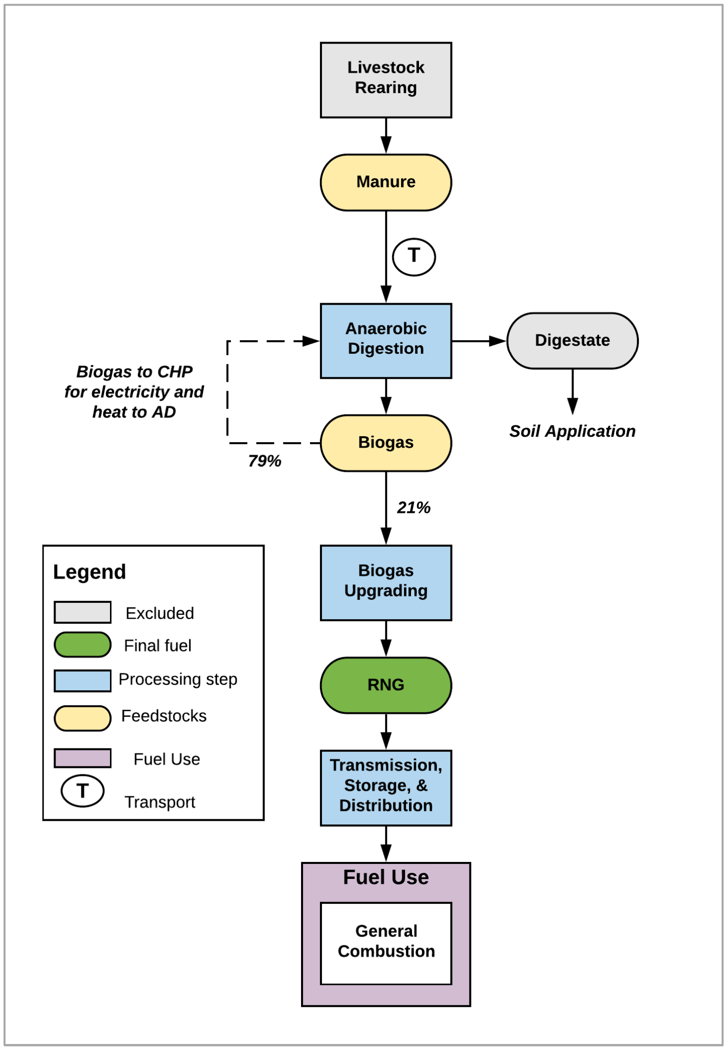

Figure 18. System boundaries for production of RNG from manure.

Upgrading of Biogas to RNG

The upgrading process for biogas from anaerobic digestion of livestock manure was assumed to be the same as that for WWT sludge and is based on an average Canadian process developed from a limited sample of Canadian producers and supplemented with literature data (CIRAIG, 2019). A summary of this process is provided in Section 8.2.

RNG Distribution and Combustion

Since there are no data available on established Canadian production and distribution supply chains for RNG, it was assumed that fuel distribution to end users would be equivalent to distribution of conventional natural gas modelled in Milestone 2 (EarthShift Global, WSP, Introspective Systems, 2019b). This is a reasonable assumption since it is expected that RNG would replace conventional natural gas in current distribution and use infrastructure.

Primary data were not available on the combustion emissions from RNG. Since the carbon contained in the fuel is biogenic, it is excluded from the CI calculations. Estimates of methane and nitrous oxide emissions associated with combustion of RNG were obtained from a summary of emissions factors for the British Columbia renewable fuels regulation (British Columbia Ministry of Environment and Climate Change Strategy, 2017). It is noted that methane and nitrous oxide emissions could vary depending on the efficiency of combustion, which is not reflected in this average case.

8.4.3 Carbon Intensity of RNG from WWT Sludge

The carbon intensity results for RNG produced from anaerobic digestion and upgrading of livestock manure are summarized in Table 76. For this average default pathway, the CI is estimated to be approximately 27 g of CO_2 eq. per MJ of fuel (HHV), which is approximately 60% lower than the CI estimated for conventional natural gas (67 g CO_2 eq./MJ). The primary contributor to the life cycle GHG emissions of the pathway is the anaerobic digestion of the organics, accounting for 37% of life cycle GHG emissions. The CI of biogas upgrading is noted to be higher than upgrading of landfill gas because the incoming biogas is assumed to have a higher methane content and thus emissions of unflared methane are higher. Feedstock transport also makes a significant contribution to total life cycle GHG emissions, accounting for 29% of emissions. This is because the manure has a high moisture content when transported to the RNG facility.

Table 74. Carbon intensity results for RNG produced from MSW organics, expressed in g CO_2 eq. per MJ of RNG (HHV).

Life Cycle Stage	Amount	Unit
Feedstock transport to RNG facility	7.9	g CO_2 eq./MJ
Anaerobic digestion	10	g CO_2 eq./MJ
Biogas upgrading	8.1	g CO_2 eq./MJ
Transport & Distribution	0.6	g CO_2 eq./MJ
Combustion	0.3	g CO_2 eq./MJ
Total	**27**	**g CO_2 eq./MJ**

8.5 Uncertainty Results for RNG

Uncertainty analysis was conducted for each of the four RNG pathways based on data quality and fit for purpose evaluations of the LCI data. Results of the Monte Carlo analysis indicate that the potential range for the CI of RNG from landfill gas is relatively tight, while the ranges for anaerobic digestion and upgrading of three different organic streams are considerably wider, particularly for the upper end of the range. This uncertainty is due to a number of factors, including the lack of specific data on the anaerobic digestion process that would be required for each different feedstock, and the potential variability in methane emissions from digestion and upgrading due to differences in practices and methane content of the biogas.

The uncertainty of the results for the RNG pathways is also shown in the violin plots in Section 12 of the report, including a comparison with the baseline CI value for conventional natural gas.

Table 75. Uncertainty analysis results for average Canadian RNG. Results based on Monte Carlo analysis with a confidence interval of 95%.

Final CI	Mean	Median	SD	Min (2.5%)	Max (97.5%)
Landfill Gas					
6.0	7.0	6.83	1.71	4.41	10.9
WWT Sludge					
31.0	38.4	37.1	10	22.6	61.6
MSW Organics					
26.4	37.2	36.1	9.7	22.5	59.6
Livestock Manure					
27.3	38.4	37.2	9.96	23.0	60.6

8.6 Data Gaps and Limitations for RNG

One of the key data gaps for RNG production in Canada is data on the specific anaerobic digestion processes that would be used for each type of organic feedstock. The data provided by CIRAIG on an average Canadian anaerobic digestion process are based on a small sample of RNG producers and are supplemented with literature values. These data are suitable for establishing an average base case unit process; however, there is considerable variability in the types of anaerobic digestion systems that could be used, and that may need to be used to accommodate specific feedstock types. More detailed work on anaerobic digestion in the GREET model indicate that the material and energy balance can vary substantially depending on the system used (Lee, Han, & Wang, 2016). There may also be variability in the material and energy inputs required for upgrading of different sources of biogas, and similar to anaerobic digestion, our model is currently limited to a single, average Canadian process based on data from a limited number of producers and supplemented with literature data. The reliance on these single average processes results in a lack of differentiation between RNG produced from different organic feedstocks, and this may not be reflective of actual conditions. It is likely that users of the Fuel LCA Modelling Tool will be able to supply data for their own anaerobic digestion and upgrading technologies and can therefore improve upon the average data used here. As such, the current CI results are generally limited to these average RNG pathways, and the uncertainty ranges provided should be used as upper and lower ranges of possible outcomes depending on variations in the technology and feedstock characteristics.

9. Hydrogen

9.1 System Boundaries and Technical Descriptions for Hydrogen Fuels

Hydrogen is currently produced globally in a variety of industrial processes as either a primary or secondary product, or in some cases as a waste product to be vented or flared to the atmosphere (Simons & Bauer, 2011). It has a wide range of physical and chemical applications, including use as a reactant in the petroleum and chemical industries, for upgrading heavy oil in oil sands applications, and to produce ammonia and methanol. It also has several engineering applications in the automotive, power generation, aerospace and telecommunications industries (Natural Resources Canada, 2015). There is considerable interest in hydrogen as a transportation fuel since there are no pollutants or GHGs emitted from hydrogen combustion.

Hydrogen is both an energy carrier and an energy source, and it is being increasingly developed for energy applications such as fuel cell electric vehicles (FCEVs). As an energy carrier, hydrogen is produced directly or indirectly from other energy sources such as fossil fuels, nuclear, hydro, solar, or wind power. The majority of hydrogen currently produced in North America is produced by steam-methane reforming (SMR), a process in which high-temperature steam is used to produce hydrogen from methane contained in sources such as natural gas. Globally, the production of hydrogen is primarily done via SMR; however, there is increasing interest in producing hydrogen from renewable sources (Olateju, Kumar, & Secanell, 2016). Methods for producing hydrogen fuel include biomass conversion, SMR of bio-based materials, and water splitting by photocatalysis, thermochemical cycles, and electrolysis. Hydrogen produced as a co-product in other processes may also be captured and used at the site of production or stored for use as a transportation fuel.

Despite growing interest in this sector, there is currently very little commercial scale production of hydrogen fuels for energy applications in Canada, although with a large and growing research and development industry, this is expected to change (MNP, 2018). Given the expected increases in development of hydrogen as a renewable fuel in Canada in the coming years, the Fuel LCA Modelling Tool for the Clean Fuel Standard (CFS) will include selected hydrogen production pathways to establish building blocks for policy makers and low carbon fuel producers to use as the industry develops. The hydrogen fuel pathways that will be included in the Fuel LCA Modelling Tool are summarized in Table 76.

Table 76. Summary of hydrogen fuel pathways including descriptions of fuel feedstock source, conversion processes, process outputs, and expected end use to be modelled.

Feedstock	Conversion Process	Outputs	End Use
• Fossil natural gas	• Steam methane reforming (SMR)	• Hydrogen • Carbon monoxide • Carbon dioxide	• Fuel cell
• Renewable natural gas (RNG)*	• Steam methane reforming (SMR)	• Hydrogen • Carbon monoxide • Carbon dioxide	• Fuel cell
• Water	• Electrolysis	• Hydrogen • Oxygen	• Fuel cell

- Syngas (wood biomass, other)	- Gasification - Catalytic reaction	- Hydrogen - Carbon monoxide - Carbon dioxide	- Fuel cell

**RNG includes natural gas produced from biogenic sources such as landfill gas*

Further descriptions of these fuels are provided in Section 9.1.1. An overview of the modelling approach for hydrogen fuels is provided in Section 9.2, and a summary of the data sources used to develop the LCI for these fuels is provided in Section 9.3.

There are a number of existing and emerging technologies in different stages of development and deployment for producing hydrogen gas for energy applications. For the purposes of the Fuel LCA Modelling Tool, we have chosen to model three basic production technologies and one energy application in order to establish the modelling building blocks for hydrogen fuels for users of the tool, and to establish default carbon intensity values for average Canadian hydrogen energy. These production processes were selected because of their current or expected use and also based on data availability. SMR is currently the dominant technology for hydrogen production in Canada (Salkuyeh, Saville, & MacLean, 2017), while interest in electrolysis is growing with a large new facility proposed for production in Québec (Air Liquide, 2019). Hydrogen from syngas was selected to provide coverage of a technology using an alternative feedstock, in this case wood biomass.

The general system boundaries for hydrogen fuels are shown in Figure 19, and include feedstock production, fuel conversion through the three selected technologies, fuel storage, transmission and dispensing, and fuel use in a hydrogen fuel cell. The use of hydrogen in fuel cells is a zero-emissions process, so that no GHG emissions are associated with hydrogen's use in a fuel cell to power a vehicle or other energy applications. More detailed descriptions of the life cycle stages for hydrogen fuels are provided in the following sections.

9.1.1 Hydrogen Production

The three hydrogen production technologies modelled for the Fuel LCA Modelling Tool are based on systems modeled by the National Renewable Energy Technology (NREL) program in the U.S. using background reports and Aspen modelling software. Because there are few large-scale operating facilities, they are based on projected production scenarios for existing technologies at different scales for different technologies. The technical descriptions below are summaries based on the NREL reports from 2013 (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013) and 2009 (Ruth, Laffen, & Timbario, 2009) from NREL.

Steam Methane Reforming (SMR)

The majority of hydrogen currently produced in North America is produced by SMR, a process in which high-temperature steam is used to produce hydrogen from a methane source, such as natural gas. Methane reacts with steam in the presence of a catalyst to produce hydrogen, carbon monoxide, and carbon dioxide. The carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen, followed by pressure-swing adsorption during which carbon dioxide and other impurities are removed to produce pure hydrogen. This process can also be used to produce hydrogen from other fuels such as ethanol, propane, or gasoline.

There are many SMR technologies available depending on the required scale of production and intended applications for the hydrogen produced. For the purposes of establishing basic SMR pathways for the Fuel LCA Modelling Tool, we have modelled a centralized SMR system that uses pipeline natural gas as feedstock, such that this pathway links up well with the work in Milestone 2 in which we modelled Canadian average pipeline natural gas.

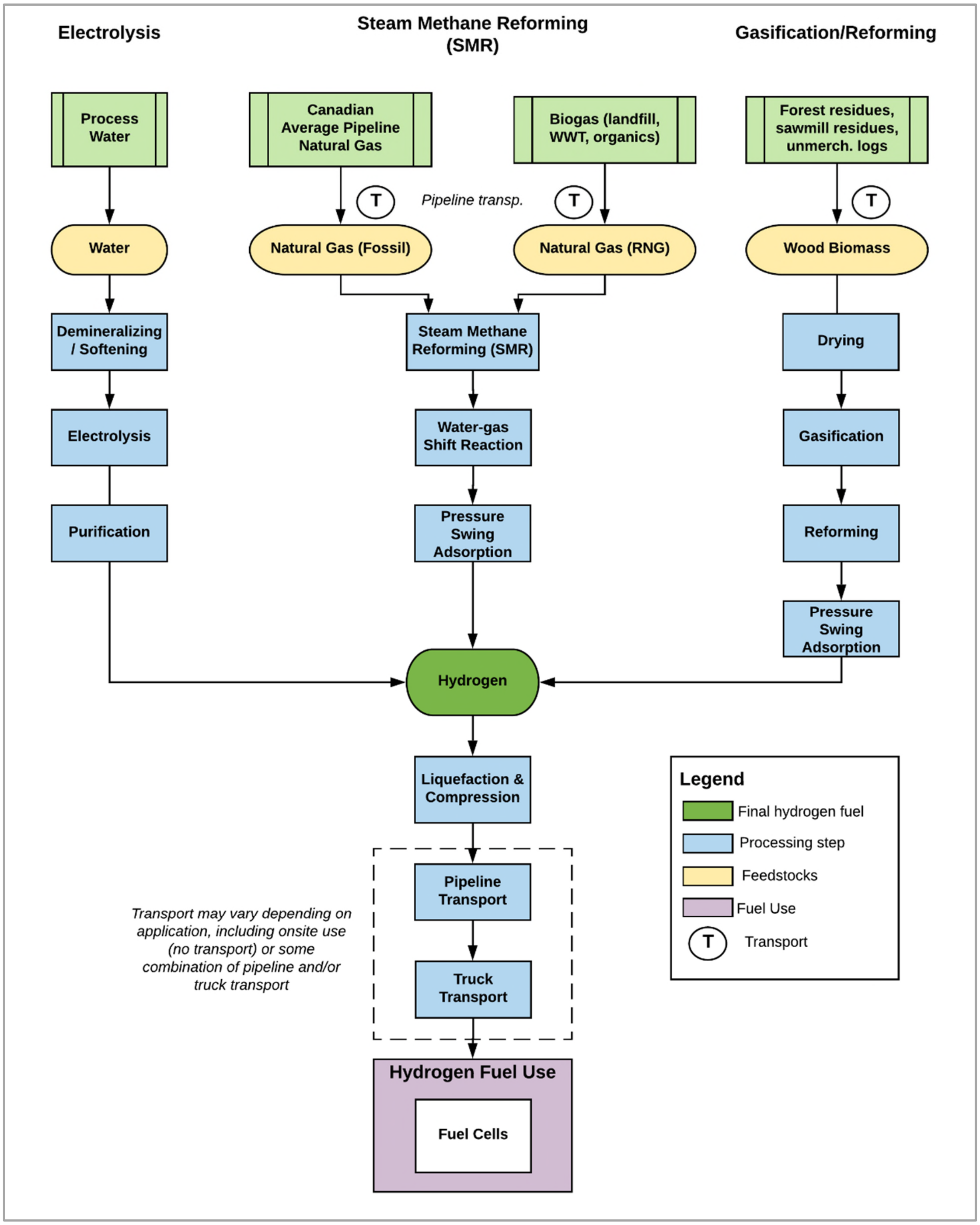

Figure 19. System boundaries and life cycle activities from extraction to use for hydrogen fuels derived from electrolysis of water, SMR of natural gas, and gasification/reforming of syngas from woody biomass.

This SMR system begins with natural gas being fed to the SMR plant via pipeline at a pressure of 450 psia. The natural gas is cleaned to remove any sulphur and then mixed with process steam and reacted over a nickel-based catalyst. This reforming reaction converts the methane to a mixture of CO and H_2 and is powered by offgas from the process and a small amount of natural gas (~10% of heating value of the offgas). Reforming is followed by a water-gas shift which converts the majority of the CO into CO_2 and H_2 (Ruth, Laffen, & Timbario, 2009). A pressure swing adsorption process is used to separate hydrogen from the other components in the shifted gas, with a part of the hydrogen product being recycled back into the adsorber to increase hydrogen concentration. Lastly, the CO and H_2 passes through a heat recovery step and is fed into a water-gas shift reactor to produce additional H_2 (Ruth, Laffen, & Timbario, 2009). The source of natural gas feedstock for SMR can either be from fossil natural gas or renewable natural gas (RNG). We will model both feedstocks for the Fuel LCA Modelling tool, basing feedstock production on pipeline natural gas as modelled in Milestone 2 (EarthShift Global, WSP, Introspective Systems, 2019b), and RNG as modelled in Milestone 3[14].

Electrolysis

Hydrogen fuel can also be produced from electrolysis. Electrolysis is the process of using electricity to separate water into hydrogen and oxygen in an electrolyzer. There are three primary types of electrolysis process used in hydrogen production, including (USOEERE, 2018):

- Alkaline – hydrogen gas is formed by passing electrons through an alkaline solution of sodium or potassium hydroxide mixed with water to form an electrolyte. A membrane is used to separate the anode from the cathode which separates the gases.
- Polymer Electrolyte Membrane - In this case, the electrolyte is a solid polymer and also acts as the membrane. Hydrogen ions flow through the polymer and combine with electrons at the cathode. Oxygen is collected at the anode.
- Solid Oxide – The solid oxide is again a solid electrolyte. In this case, steam combines with electrons at high temperature (500-800 degrees C) at the porous cathode to form hydrogen gas which passes through the cathode to be collected. The negatively charged oxygen ions pass through the solid electrolyte and react at the anode to form oxygen gas.

Similar to SMR, there are many different electrolysis technologies available to produce hydrogen using a number of different energy sources and sources of water. For the purposes of establishing a basic electrolysis pathway in the Fuel LCA Modelling Tool, we have modelled a centralized electrolysis plant using an alkaline process powered by grid electricity and using potassium hydroxide (KOH) as the electrolyte. This process represents a scaled-up version of a distributed electrolysis technology (1,500 kg hydrogen/day) with a production capacity of 52,300 kg/day (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013). Process water is demineralized and softened before being passed into the electrolyzer. The electrolyzer produces hydrogen and oxygen which are collected and fed into a gas/lye (KOH) separator system. The lye is produced and re-used within a closed-loop cycle. Saturated hydrogen gas from the hydrogen/lye separator is fed to a gas scrubber subsystem which purifies the hydrogen. The hydrogen gas is held in a small gas holder unit and is compressed to 435 psig. Following compression, the residual

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[14] The modelling of RNG is delayed until August/September of 2019 while a separate contractor collects data from Canadian RNG producers. At that time, the RNG hydrogen pathway will be completed.

oxygen is removed by the deoxidizer unit and the hydrogen gas is then dried and exits the process at 99.9998% purity (Ruth, Laffen, & Timbario, 2009).

Gasification and Reforming

Hydrogen can be produced from syngas that is derived from several different feedstocks, and there are several different types of technologies that can be used to convert syngas to hydrogen gas. For the purposes of the Fuel LCA Modelling Tool, we have modelled a system which converts woody biomass to hydrogen via a series of process steps, including gasification, catalytic steam reforming, and purification (Ruth, Laffen, & Timbario, 2009). This process was chosen because data were readily available and because the conversion process could be easily connected with existing wood biomass feedstock processes in the Fuel LCA Modelling Tool. In this conversion process, the incoming woody biomass is dried to 12% moisture content using a rotary dryer. The rotary dryer is powered primarily by the combustion of char that is produced during the gasification process. The endothermic gasification unit is powered by circulation of hot synthetic olivine, and the resulting gas is passed through cyclone separators to remove particulates, ash, and sand. Following gasification, the gas is passed through a similar process of reforming and water-gas shift reactions that is used in SMR technology. An adsorber unit is used to separate the hydrogen from the other components in the shifted gas stream (primarily CO_2 and unreacted CO, CH_4, and other hydrocarbons) (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013).

9.1.2 Distribution

Distribution of hydrogen gas from the production facility to the end user can be done by pipeline, truck, or some combination of the two modes. A transmission pipeline would extend from the production facility to the “city gate”, or some central distribution point from which the hydrogen is transported to the end user via truck. The pipeline system requires a compressor to increase hydrogen pressure from its production level to the pressure at the terminus of the transmission line (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013). Storage is assumed to be done using geologic formations that are adjacent to the production facility. A compressor is used to extract the hydrogen from storage and push it into the pipeline.

Truck transport of gaseous hydrogen involves the storage of hydrogen, the extraction of hydrogen from storage with a compressor, and transport in a tube trailer truck. Transport of liquid hydrogen by truck involves liquefaction of the hydrogen prior to transport, storage of liquid hydrogen in cryogenic storage tanks and transport via cryogenic trucks. The liquefaction of hydrogen is assumed to be powered by grid electricity. In the Fuel LCA Modelling Tool, the user will be able to modify this to other energy sources such as natural gas or other fuels.

Note: As hydrogen is extremely flammable and can be explosive when exposed to air in enclosed areas, hydrogen sensors are likely to be used at many places in the production, transmission and distribution facilities. As the sensors are considered to be part of the infrastructure, they are excluded from the inventory.

In some instances, hydrogen production may be done onsite, and distribution would not be required, for example if an electrolyzer is installed onsite.

9.1.3 Hydrogen Use

Hydrogen use is assumed to be in proton exchange membrane fuel cells for vehicle transportation. These cells operate essentially the same as the polymer electrolyte membrane electrolysis process in reverse, so instead of requiring electricity and water to create hydrogen, hydrogen is used to create electricity and water (Dhanushkodi, Mahinpey, Srinivasan, & Wilson, 2008). Therefore, there are no direct greenhouse gas emissions associated with use of hydrogen in fuel cell technology (Ahmadi & Kjeang, 2016) .

Use scenarios in the Fuel LCA Modelling Tool will be defined by the user locations and transmission and distribution distances.

Based on data from GREET, Table 77 summarizes some key parameters for final hydrogen fuel (Harrison, Remick, Martin, & Hoskin, 2010).

Table 77. Energy content and density values for gaseous hydrogen

Property	By Volume	By Mass
HHV	12.8 MJ/m^3	141.9 MJ/kg
Density	90.1 g/m^3	-

9.2 Modelling Approach for Hydrogen Fuels

The following sections provide a brief overview of the modelling approach for hydrogen fuels, as well as discussion of some key methodological issues to be addressed in the modelling.

9.2.1 Development of Unit Process Building Blocks

The modelling work in Milestone 3 relies heavily on fossil fuel unit processes that were developed in Milestone 2, including natural gas as an input to SMR production of hydrogen, fuel inputs to operate machinery and equipment (e.g. diesel, natural gas, etc.) and transportation processes (e.g. trucks, rail, pipelines). In addition, unit processes for wood biomass feedstocks and RNG feedstocks that are being developed in Milestone 3 will be used as building blocks in the hydrogen fuel pathways. These unit processes were used to model average hydrogen production. In addition, these unit process building blocks will be available in the ECCC Fuels database and can be incorporated into the hydrogen fuel pathway models or other pathways as needed.

9.2.2 Regional Variation

At present there is very little commercial production of hydrogen fuel specifically for energy applications in Canada, although hydrogen produced from existing commercial scale operations could be used in fuel cells or injected in pipelines to be blended as a fuel. The primary aspect of hydrogen production that will vary from region to region is the background energy system, such as variations in electricity grids providing energy to fuel conversion and compression processes. In addition, the provision of feedstocks for hydrogen production may vary from region to region within Canada, for example differences in carbon intensity for production of RNG or wood biomass feedstocks. The sourcing of regional/provincial feedstocks could also influence transport distances and modes for feedstock delivery and final fuel delivery.

For the development of default carbon intensity values for Canadian hydrogen fuels, average Canadian conditions and energy sources were used. Beyond these default calculations, users will have the ability to copy and modify the default processes and use alternative building blocks available in the tool (e.g. provincial electricity grid, a different wood biomass feedstock) and/or build new unit processes to pull into the hydrogen pathway models.

A number of basic building blocks are available in the Fuel LCA Modelling Tool to allow users to represent these differences in the modelling as much as possible within the confines of the available data. For example, forest harvesting data is available only for Western and Eastern Canada, and not a provincial level. As such, the wood biomass feedstocks used in hydrogen production are based on a unit process from either of these two regions, or the unit process for Canadian average harvesting. With respect to background energy systems, electricity grid carbon intensities are available at a provincial level based on work completed in Milestone 2, as are some fuels (e.g. diesel), and can be incorporated into the unit processes available for hydrogen fuels. For example, in modelling the production of hydrogen from electrolysis in British Columbia, a user could copy the Canadian default pathway and change the electricity grid to British Columbia electricity to power the process. Differences in regional electricity grids will be particularly relevant for the electrolysis pathway, as electricity is a key input. Users will be able to choose between different electricity grids by province or can choose a specific direct electricity source in the modelling tool, for example to use electricity directly from wind power.

9.3 Life Cycle Inventory for Hydrogen Fuels

9.3.1 Steam Methane Reforming (SMR)

Feedstock Production

Production of hydrogen via SMR was modeled with both fossil natural gas and renewable natural gas feedstocks. The carbon intensity of the upstream production of fossil natural gas was obtained from the Canadian average pathway for pipeline specification natural gas modeled in Milestone 2 (EarthShift Global, WSP, Introspective Systems, 2019b). This includes the extraction, processing, and transmission of fossil natural gas from Western Canada to hydrogen production locations via pipeline. For the purposes of the current version of the report, a recently published carbon intensity value for RNG in Canada was used to characterize the carbon intensity of producing RNG. In April of 2019, RNG produced by FortisBC was added to the Low Carbon Fuel Standard in British Columbia with a verified CI of 11 g CO_2 eq. per MJ (CISION, 2019). This RNG is produced from biogas derived from municipal organic waste in landfills and from farm wastes. Since the carbon contained in RNG is considered biogenic, the process emissions of carbon dioxide are excluded from the CI calculation. From the production gate, RNG is assumed to follow the same transmission path to hydrogen producers as fossil natural gas (i.e. average Canadian storage and pipeline transmission). The final carbon intensity of the upstream production of RNG will be obtained from the Milestone 3 modelling work that will be completed separately based on data collected by another ECCC contractor. This work will include multiple sources of RNG that can be incorporated into the Fuel LCA Modelling Tool, and is expected to be completed in August 2019.

Fuel Conversion

At present there are no publicly available Canadian-specific LCI data to model production of hydrogen gas via SMR of natural gas. The conversion of both fossil natural gas and renewable natural gas to hydrogen using SMR were modeled using data compiled by the National Renewable Energy Laboratory (NREL) in the U.S. for a centralized SMR facility using natural gas delivered by pipeline (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013). Although the GHGenius calculator includes pathways for hydrogen from SMR, they are not Canadian-specific and are based primarily on literature sources and theoretical systems. It was determined that the NREL data are potentially more representative of recent systems.

The inputs for production of 1 kg and 1 MJ of hydrogen gas via a centralized facility for SMR of natural gas are summarized in Table 78 below.

Table 78. Process inputs for production of 1 kg and 1 MJ of hydrogen via SMR (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013).

Input	Per kg H_2	Per MJ H_2*
Hydrogen Production		
Natural gas (feedstock)	165 MJ	1.16 MJ
Electricity	0.57 kWh	0.004 kWh
Process water	3.36 gal	0.024 gal
Cooling water	1.50 gal	0.011 gal
Outputs		
Carbon dioxide (process)	12,060 g	85.1 g

**HHV of hydrogen gas is 141.9 MJ/kg, so 1 MJ of hydrogen is 0.007 kg*

The carbon intensities for electricity and natural gas were obtained from the results of the Milestone 2 work on carbon intensity of Canadian fossil fuels (EarthShift Global, WSP, Introspective Systems, 2019b). The default carbon intensity of hydrogen produced via SMR was modeled using a Canadian average electricity grid; however, users of the Fuel LCA Modelling tool will be able to modify the electricity source to calculate the carbon intensity for hydrogen production in different provinces.

9.3.2 Electrolysis

At present there are no publicly available Canadian-specific LCI data to model production of hydrogen gas via electrolysis of water. The conversion of water to hydrogen using electrolysis was modeled using data compiled by the National Renewable Energy Laboratory (NREL) in the U.S. for a centralized electrolysis facility powered by grid electricity (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013).

The process inputs for production of 1 kg and 1 MJ of hydrogen via a centralized facility for electrolysis are summarized in Table 79 below.

Table 79. Process inputs per kg and MJ of hydrogen produced via electrolysis (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013).

Input	Per kg H_2	Per MJ H_2*
Hydrogen Production		
Electricity	50 kWh	0.35 kWh
Process water	2.94 gal	0.021 gal
Cooling water	0.11 gal	0.00077 gal

**HHV of hydrogen gas is 141.9 MJ/kg, so 1 MJ of hydrogen is 0.007 kg*

The carbon intensity for grid electricity was obtained from the results of the Milestone 2 work on carbon intensity of Canadian fossil fuels (EarthShift Global, WSP, Introspective Systems, 2019b).

The default carbon intensity of hydrogen produced via electrolysis was modeled using a Canadian average electricity grid, as well as for two specific provincial grids to show the potential variability of the CI based on the nature of the grid. In addition, users of the Fuel LCA Modelling tool will be able to modify the electricity source to calculate the carbon intensity for hydrogen production in different provinces, or using direct electricity sources to the electrolyzer such as wind power.

9.3.3 Gasification/Reforming of Syngas

At present there are no publicly available Canadian-specific LCI data available to model production of hydrogen gas via reforming of syngas. The conversion of syngas to hydrogen was modeled using data compiled by the National Renewable Energy Laboratory (NREL) in the U.S. for a centralized facility for woody biomass gasification and reforming (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013).

The inputs for production of 1 kg and 1 MJ of hydrogen via a centralized facility for reforming of syngas from woody biomass are summarized in Table 80 below.

Table 80. Process inputs to production of 1 kg and 1 MJ of hydrogen via gasification and reforming of wood biomass (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013).

Input	Per kg H_2	Per MJ H_2*
Hydrogen Production		
Wood biomass (feedstock)	13.5 kg	0.095 kg
Natural gas	6.22 MJ	0.044 MJ
Electricity	0.98 kWh	0.0069 kWh
Process water	1.32 gal	0.009 gal
Cooling water	79.3 gal	0.56 gal
Outputs		
Carbon dioxide (process)**	30,720 g	216.5 g

**HHV of hydrogen gas is 141.9 MJ/kg, so 1 MJ of hydrogen is 0.007 kg*

***Process carbon dioxide emissions are from a biogenic source and are therefore excluded from the CI calculations*

The carbon intensity for grid electricity and natural gas were obtained from the results of the Milestone 2 work on carbon intensity of Canadian fossil fuels (EarthShift Global, WSP, Introspective Systems, 2019b), and the carbon intensity for production of the wood biomass feedstock were obtained from modelling work on low carbon solid fuels in Milestone 3, including sawdust from average Canadian sawmilling, wood chips from forest harvest residues, and wood chips from unmerchantable roundwood.

The default carbon intensity of hydrogen produced via reforming of syngas was modeled using a Canadian average electricity grid and Canadian average wood biomass feedstocks; however, users of the Fuel LCA Modelling tool will be able to modify the electricity source to calculate the carbon intensity for hydrogen production in different provinces, or choose wood biomass feedstocks specifically from Western or Eastern Canada.

9.3.4 Distribution

Transmission of the natural gas is modeled as part of the Canadian average natural gas detailed in Milestone 2. Given the early stage of hydrogen fuel development for energy applications in Canada, there are no established hydrogen pipeline distribution networks in Canada, and relatively small distribution networks via truck. Depending on the facility type, size, and location, the distribution of hydrogen could be done via pipeline and/or truck, and truck transport could be done for gaseous hydrogen or liquid hydrogen. For the purposes of establishing low carbon fuel pathway templates, we have modeled generic transmission distances of 100 km via each of the possible methods to establish building blocks for these activities in the model. For the default Canadian average hydrogen results we have assumed transport by gas truck.

Once delivered to service stations, there is also energy consumption associated with the storage, compression, and dispensing of hydrogen fuel. The LCI data for different forms of transmission, distribution, and fuel dispensing were obtained from NREL in the U.S. (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013) and are summarized in Table 81 below.

Table 81. Energy inputs per kg and per MJ of hydrogen dispensed for hydrogen transmission via pipeline or truck and dispensing of hydrogen fuel at different types of fuel stations (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013).

Input	Per kg H_2	Per MJ H_2*
Pipeline Transmission		
Electricity – compressor	0.56 kWh	0.0039 kWh
Electricity – storage	0.01 kWh	0.00007
Truck Transport (gaseous)		
Electricity – terminal	1.31 kWh	0.92 kWh
Electricity – storage	0.01 kWh	0.00007 kWh
Diesel – truck	0.0589 gal	0.0004 gal
Truck Transport (liquid)		
Electricity - liquefaction	8.5 kWh	0.060 kWh
Electricity – terminal	0.03 kWh	0.00021 kWh
Diesel - truck	0.0076 gal	0.00005 gal
Dispensing		
Station – distributed from pipeline (300 psi)	4.4 kWh	0.031 kWh
Station – centralized from pipeline (300 psi)	4.4 kWh	0.031 kWh
Central – 220 psi inlet pressure	2.1 kWh	0.015 kWh
Central - gaseous	0.51 kWh	0.0036 kWh
Cryo-compressed dispensing	0.49 kWh	0.0034 kWh

**HHV of hydrogen gas is 141.9 MJ/kg, so 1 MJ of hydrogen is 0.007 kg*

***Converted from 0.0589 gal of diesel based on HHV of diesel is 45.8 MJ/kg, density is 3.21 kg/gal*

The carbon intensity for electricity and diesel were obtained from the results of the Milestone 2 work on the carbon intensity of Canadian fossil fuels (EarthShift Global, WSP, Introspective Systems, 2019b).

9.4 Carbon Intensity Results for Hydrogen Fuels

Carbon intensity results for hydrogen fuels are summarized in the following sections, including comparative pathway results and contribution analysis results for each type of hydrogen production.

9.4.1 Steam Methane Reforming

The carbon intensity results for various pathways of hydrogen produced from SMR are summarized in Table 82, including SMR of fossil natural gas and SMR of RNG.

The CI value for Canadian average hydrogen produced from SMR of fossil natural gas is between 104 and 114 g CO_2 eq. per MJ. This value varies somewhat depending on the mode of fuel distribution, with the use of liquid truck delivery resulting in a higher CI of 114 g CO_2 eq. per MJ due to the extra step of liquefaction, the use of pipeline delivery resulting in a lower CI of 104 g CO_2 eq. per MJ, and the use of gas truck delivery resulting in a CI of 110 g CO_2 eq. per MJ.

Table 82. Canadian average carbon intensity values for hydrogen fuel produced from SMR from fossil natural gas and renewable natural gas with alternative transmission modes, expressed in g CO_2 eq./MJ of fuel used in a fuel cell.

Hydrogen Fuel Pathway	Carbon Intensity (g CO_2 eq./MJ)
SMR of Fossil Natural Gas	
Hydrogen, from SMR of natural gas, gas truck delivery	110
Hydrogen, from SMR of natural gas, liquid truck delivery	114
Hydrogen, from SMR of natural gas, pipeline transmission	104
SMR of Renewable Natural Gas (from landfill gas)	
Hydrogen, from SMR of RNG from landfill gas, gas truck delivery	15
Hydrogen, from SMR of RNG from landfill gas, liquid truck delivery	18
Hydrogen, from SMR of RNG from landfill gas, pipeline transmission	7.9

The CI value for Canadian average hydrogen produced from SMR of RNG from landfill ranges from 7.9 to 18 g CO_2 eq. per MJ, again depending on the distribution mode. Comparing the Canadian average CI for hydrogen from SMR using gas truck delivery, the use of RNG as the feedstock results in an 86% decrease in life cycle GHG emissions. This is due primarily to the exclusion of process carbon dioxide emissions for SMR of RNG due to their biogenic source.

Contribution analysis results for Canadian average hydrogen produced from SMR of fossil natural gas and RNG delivered by gas truck are summarized in Table 83. Direct emissions of carbon dioxide from the SMR process account for 77% of life cycle GHG emissions, followed by feedstock production and transport which accounts for approximately 15% of emissions. In contrast to hydrogen from SMR of fossil natural gas, the carbon intensity for hydrogen from RNG is mainly due to the production of the RNG feedstock, as direct process carbon dioxide emissions are excluded from the CI due to their biogenic nature. For all other aspects of the life cycle besides feedstock production and direct process emissions, the CI is the same.

Table 83. Contribution analysis of the Canadian average carbon intensity of hydrogen fuel produced from SMR from fossil natural gas delivered by gas truck, expressed in g CO_2 eq./MJ of fuel used in a fuel cell.

Life Cycle Stage	Fossil Natural Gas (g CO_2 eq./MJ)	Renewable Natural Gas (g CO_2 eq./MJ)
Natural gas (feedstock for SMR)	15	5.8
Natural gas feedstock transmission	0.8	0.8
Process electricity	0.7	0.7
Direct process carbon dioxide emissions*	85	0

Geological storage	0.01	0.01
Truck transport	7.4	7.4
Fuel dispensing	0.6	0.6
Total	**110**	**15**

**Note that there are direct process emissions of CO_2 during SMR of RNG, but they are from a biogenic source and are therefore excluded from the CI calculations.*

9.4.2 Electrolysis

The carbon intensity results for various pathways of hydrogen produced from electrolysis in Canada are summarized in Table 83Table 84, including production from different background electricity systems to demonstrate potential variability in the results.

Table 84. Carbon intensity values for hydrogen fuel produced from electrolysis from fossil natural gas and renewable natural gas with alternative transmission modes, expressed in g CO_2 eq./MJ of fuel used in a fuel cell.

Hydrogen Fuel Pathway	Carbon Intensity (g CO_2 eq./MJ)
Hydrogen from Electrolysis – Canadian Average	
Hydrogen, from electrolysis, pipeline transmission {CA}	65
Hydrogen, from electrolysis, liquid truck delivery {CA}	75
Hydrogen, from electrolysis, gas truck delivery {CA}	71
Hydrogen from Electrolysis – Alberta	
Hydrogen, from electrolysis, pipeline transmission {CA-AB}	350
Hydrogen, from electrolysis, liquid truck delivery {CA-AB}	406
Hydrogen, from electrolysis, gas truck delivery {CA-AB}	360
Hydrogen from Electrolysis – British Columbia	
Hydrogen, from electrolysis, pipeline transmission {CA-BC}	29
Hydrogen, from electrolysis, liquid truck delivery {CA-BC}	34
Hydrogen, from electrolysis, gas truck delivery {CA-BC}	36

The Canadian average CI for hydrogen from electrolysis is between 65 and 75 g CO_2 eq. per MJ, with the differences in CI being accounted for by different fuel transmission modes. These CI results are based on the use of electricity derived from the average Canadian electricity grid. Since electricity is the primary input to hydrogen production via electrolysis, the CI results are very sensitive to the electricity grid used. To demonstrate the potential variability, CI results are presented in Table 84 for a province with a fossil fuel-based grid (Alberta) and a hydropower-based grid (British Columbia). The results indicate that the CI of hydrogen from electrolysis could range from as low as 29 g CO_2 eq. per MJ up to 406 g CO_2 eq. per MJ.

The contribution analysis summarized in Table 85 reaffirms this observation about the importance of electricity source, showing that for hydrogen produced from electrolysis from a Canadian average grid, the upstream emissions from electricity production account for nearly 85% of life cycle GHG emissions. Results in this table also show the contribution analysis for hydrogen with liquid truck delivery, where liquefaction of hydrogen prior to distribution accounts for 14% of life cycle GHG emissions.

Table 85. Contribution analysis of the Canadian average carbon intensity of hydrogen fuel produced from electrolysis delivered by liquid truck, expressed in g CO_2 eq./MJ of fuel used in a fuel cell.

Life Cycle Stage	Carbon Intensity (g CO_2 eq./MJ)
Electricity - process	63
Geological storage	0.01
Liquefaction	11
Truck transport - liquid	0.07
Fuel dispensing	0.6
Total	**75**

9.4.3 Gasification and Reforming of Syngas

The carbon intensity results for various pathways of hydrogen produced from gasification and reforming of syngas from wood biomass in Canada are summarized in Table 86, including production from different sources of wood biomass feedstocks.

Table 86. Canadian average carbon intensity values for hydrogen fuel produced from gasification and reforming of various wood biomass feedstocks and alternative transmission modes, expressed in g CO_2 eq./MJ of fuel used in a fuel cell.

Hydrogen Fuel Pathway	Carbon Intensity (g CO_2 eq./MJ)
Hydrogen from Gasification and Reforming of Sawdust	
Hydrogen, from gasification and reforming, from sawdust, gas truck delivery	15
Hydrogen, from gasification and reforming, from sawdust, liquid truck delivery	19
Hydrogen, from gasification and reforming, from sawdust, pipeline transmission	8.4
Hydrogen from Gasification and Reforming of Harvest Residues	
Hydrogen, from gasification and reforming, from harvest residues, gas truck delivery	16
Hydrogen, from gasification and reforming, from harvest residues, liquid truck delivery	20
Hydrogen, from gasification and reforming, from harvest residues, pipeline transmission	9.8
Hydrogen from Gasification and Reforming of Unmerchantable Roundwood	
Hydrogen, from gasification and reforming, from unmerchantable roundwood, gas truck delivery	17
Hydrogen, from gasification and reforming, from unmerchantable roundwood, liquid truck delivery	21
Hydrogen, from gasification and reforming, from unmerchantable roundwood, pipeline transmission	10

Results show that the Canadian average CI for hydrogen produced from gasification and reforming of syngas from wood biomass ranges between 8.4 and 21 g CO_2 eq. per MJ depending on wood biomass feedstock source and final fuel transmission mode. The use of wood chips from harvest residues with fuel transmission via pipeline resulted in the lowest Canadian average CI, while the use of wood chips from unmerchantable logs with fuel transmission via liquid truck resulted in the highest Canadian average CI.

The contribution analysis for hydrogen produced from gasification and reforming of syngas from sawdust and transmitted via pipeline shown in Table 87 indicate that upstream emissions from the processing and delivery of sawdust from Canadian sawmills made the largest contribution to life cycle GHG emissions at approximately 45% of the total. It is also noted that biogenic carbon dioxide emissions from the reforming process were excluded from the CI calculations.

Table 87. Contribution analysis of the Canadian average carbon intensity of hydrogen fuel produced from gasification and reforming of syngas from sawdust and delivered by pipeline transmission, expressed in g CO_2 eq./MJ of fuel used in a fuel cell.

Hydrogen Fuel Pathway	Carbon Intensity (g CO_2 eq./MJ)
Sawdust feedstock	3.2
Natural gas - process	2.7
Electricity - process	1.2
Direct process carbon dioxide emissions*	0
Geological storage	0.01
Pipeline transmission	0.7
Fuel dispensing	0.6
Total	**8.4**

**Note that there are direct process emissions of CO_2, but they are from a biogenic source and are therefore excluded from the CI calculations.*

9.4.4 Uncertainty Analysis

Uncertainty analysis was conducted for Canadian average hydrogen using Monte Carlo analysis. Results of the uncertainty analysis for hydrogen are shown in the violin plots in Section 12 and discussed relative to the uncertainty of other low carbon fuels in that section. Below in Table 88 the key results of the uncertainty analysis for hydrogen from each of the three sources are summarized.

Table 88. Uncertainty analysis results for average Canada hydrogen fuel. Results based on Monte Carlo analysis with a confidence interval of 95%.

Final CI	Mean	Median	SD	Min (2.5%)	Max (97.5%)
Hydrogen, from electrolysis, gas truck delivery, {CA}					
71.2	74.1	72.6	17.6	45.4	116
Hydrogen, from SMR of natural gas, gas truck delivery {CA}					
110	112	111	12.8	89.1	138
Hydrogen, from SMR of RNG from landfill gas, gas truck delivery {CA}					
15	16.8	15.5	5.29	-0.082	123
Hydrogen, from gasification and reforming of syngas, from sawdust {CA}					
16.4	16.8	15.9	5.23	9.73	29.5

Results of the uncertainty analysis show that there is greater uncertainty around the result for hydrogen from electrolysis, which has a wider range of potential outcomes. This is due to the fact that the carbon intensity of hydrogen from electrolysis is heavily influenced by the background electricity grid and the efficiency of the electrolysis process and shifts in these inputs can push the results higher or lower significantly. The uncertainty for hydrogen from SMR of RNG is also high, due to the relative uncertainty in the CI of producing RNG from landfill gas, and coupled with the uncertainty around the SMR conversion technology for RNG sources.

9.4.5 Data Gaps and Limitations for Hydrogen Fuels

The limitations of modelling the CI for Canadian hydrogen fuels are largely based on the lack of commercial-scale activity in this sector which means that assumptions must be made about technology and about the structure of the industry. Changes in technology efficiency (e.g. of electrolysis), changes in feedstock and energy systems, and changes in fuel distribution could lead to significant differences in the CI of average hydrogen fuel in Canada. Fortunately, as these details evolve over time with growth in the industry, the basic building blocks are in place for the primary hydrogen production technologies and feedstocks to facilitate the building of new models to calculate more representative CI values for Canadian hydrogen production activities.

10. Solid Low Carbon Fuels

10.1 System Boundaries and Technical Descriptions for Solid Low Carbon Fuels

Solid fuels can be produced from several different feedstocks in Canada, including wood biomass, agricultural residues, and industrial and municipal solid wastes. These solid fuels typically take the form of energy-dense pellets but may also include raw material precursors and process co-products (e.g. wood chips, corn stover). Solid low carbon fuels are typically used as energy feedstocks in industrial boilers and furnaces, for institutional or residential space heating, and for small-scale and large-scale electricity generation in thermal power plants.

The solid low carbon fuels that will be included in the Fuel LCA Modelling Tool are summarized in Table 89. Most of these fuels are derived from wood biomass feedstocks of various types, with the one exception being corn stover.

Table 89. Summary of solid low carbon fuel pathways including descriptions of fuel feedstock source, conversion processes, process outputs, and expected end use to be modelled.

Fuel	Feedstock	Conversion Process	End Use
Grade A1 Wood Pellets	• Clean sawmill residues	• Drying • Pelletization	• Heating • Electricity
Grade A2/B1/B2 Wood Pellets	• Unmerchantable standing trees • Forest harvest residues • Other sawmill residues • Construction &Demolition (C&D) waste	• Chipping • Drying • Pelletization	• Heating • Electricity
Black wood pellets (thermally treated wood pellets)	• Unmerchantable standing trees • Forest harvest residues • Sawmill residues • Construction & Demolition (C&D) waste	• Steam treatment • Torrefaction • Pelletization	• Electricity
Wood chips	• Unmerchantable standing trees • Sawmill residues	• Chipping • Drying	• Heating
Crop residues	• Corn stover	• Drying • Pelletization	• Heating

Further descriptions of these fuels are provided in Section 10.1.1. An overview of the modelling approach for solid low carbon fuels is provided in Section 10.2, and a summary of the data sources that were used to develop the LCI for these fuels is provided in Section 10.3.

10.1.1 Wood Biomass Fuels

There are several low carbon fuel feedstocks produced at various points within the Canadian forest sector. The Canadian forest sector is a highly-integrated system of products and processes all originating from the harvest of standing timber in Canadian forests and culminating in a wide variety of midstream uses and end products and uses. Within this flow of wood fibre, a number of solid low carbon fuel feedstocks are produced, including:

- Wood chips produced directly from harvested forest biomass (roundwood);
- Wood chips produced from primary forest harvest residues (i.e. branches, tops, also called bush residual etc.);
- Wood chips or other residuals from sawmilling (e.g. wood chips, bark, sawdust, shavings, also called hog fuel if used on site); and
- Used wood obtained from construction and demolition (C&D) waste streams.

Some of these wood biomass feedstocks may be used directly for energy in forest sector applications (e.g. for drying energy in sawmills), as a source of heat or steam in other industrial applications, or used as feedstock by industries complimentary to the forest sector such as pellet mills to produce more energy-dense fuels with a wide range of applications from residential space heating to large-scale electricity generation.

The Canadian wood pellet industry is a growing sector of the economy that is largely export driven, with major markets in Europe, the United States, and increasingly Asia (Bradburn & Lakhdari, 2017). At the end of 2016 there were 30 operational wood pellet plants in Canada, and as of early 2019 there are 46 operational wood pellet plants in Canada. A summary of currently operation plants is provided in Table 90. Bulk pellets are produced primarily for export markets, while bagged pellets are produced primarily for domestic heating applications.

Although there are operational wood pellet plants in several Canadian provinces, approximately 70% of Canadian wood pellet production occurs in British Columbia, with other top producing provinces being Québec, Ontario, Alberta, and New Brunswick (Bradburn, 2014). At present there is no commercial-scale production of thermal treated (black) wood pellets.

Table 90. Operational wood pellet plants in Canada in 2019, shown by location, share of bulk vs. bagged pellet production, and annual capacity in metric tonnes (Canadian Biomass Magazine, 2019).

Plant Location	Province	Bulk/Bagged (%)	Capacity (tonnes/year)
Prince George	British Columbia	100/0	350,000
Armstrong	British Columbia	80/20	72,000
Burns Lake	British Columbia	100/0	380,000
Strathnaver	British Columbia	100/0	230,000
Williams Lake	British Columbia	100/0	210,000
Houston	British Columbia	100/0	230,000
Lavington	British Columbia	100/0	300,000
Smithers	British Columbia	100/0	125,000
Vanderhoof	British Columbia	90/10	185,000
Princeton	British Columbia	70/30	110,000
Vanderhoof	British Columbia	NA	30,000
Chetwynd	British Columbia	100/0	100,000
Fort St. John	British Columbia	100/0	75,000
Terrace	British Columbia	100/0	75,000
Entwistle	Alberta	100/0	400,000
Grande Cache	Alberta	60/40	15,000
Manning	Alberta	80/20	15,000
La Crete	Alberta	80/20	140,000
Slave Lake	Alberta	50/50	60,000
Swan River	Manitoba	100/0	2,000

Elm Creek	Manitoba	80/20	10,000
Atikokan	Ontario	90/10	110,000
Thunder Bay	Ontario	100/0	45,000
St. Marys	Ontario	60/40	10,000
Hearst	Ontario	15/85	15,000
Dunkalk	Ontario	25/75	15,000
Springford	Ontario	10/90	25,000
New Liskeard	Ontario	75/25	80,000
Becancour	Quebec	100/0	15,000
Lac-Megantic	Quebec	NA	120,000
Sacre-Coeur	Quebec	NA	25,000
St-Felicien	Quebec	5/95	120,000
Shawinigan-Suyd	Quebec	<1/99	55,000
St. Paulin	Quebec	NA	60,000
Papineauville	Quebec	NA	34,000
Saint-Hyacinthe	Quebec	<1/99	30,000
Lac au Saumon	Quebec	100/0	47,000
Saint-Jean-Port-Joli	Quebec	70/30	7,000
Bristol	New Brunswick	15/85	40,000
St-Quentin	New Brunswick	40/60	90,000
Tracyville	New Brunswick	20/80	10,000
Belledune	New Brunswick	100/0	100,000
Shubenacadie	Nova Scotia	15/85	50,000
Upper Musquodobit	Nova Scotia	100/0	100,000
Summerford	Newfoundland & Labrador	NA	12,000
Bishop's Falls	Newfoundland & Labrador	NA	1,000

The system boundaries and process flow for wood biomass solid fuels are summarized in Figure 20. This includes various wood biomass feedstocks from different activities in the forest sector supply chain, as well as waste wood obtained from C&D solid waste streams. Note that "Bioenergy Harvest" in Figure 20 refers to incremental harvesting of standing forest biomass above and beyond the business as usual commercial harvesting for lumber.

Wood Biomass Feedstocks

Canadian wood pellet producers use a variety of feedstocks depending on the intended use of the pellets. As shown in Table 91, the most commonly used feedstock is sawmill residues (90%), followed by hog fuel and whole roundwood.

Table 91. Wood pellet plant feedstocks used in Canadian wood pellet plants in 2016, in metric tonnes (Bradburn & Lakhdari, 2017).

	Bush Residual	Mill residues	Hog Fuel	Roundwood	Waste Wood	Total
AB	0	113,000	0	0	0	113,000
BC	21,000	1,733,500	136,000	96,000	16,000	2,002,500
SK	0	0	0	0	0	0
ON	0	87,000	0	0	9,000	96,000
QC	0	350,000	0	0	0	350,000
NB	0	192,000	0	0	0	192,000

NS	0	30,000	0	0	0	30,000
NL	0	200	0	0	0	200
Total	**21,000**	**2,505,700**	**136,000**	**96,000**	**25,000**	**2,783,700**
Canada	***0.75%***	***90%***	***4.8%***	***3.4%***	***0.9%***	

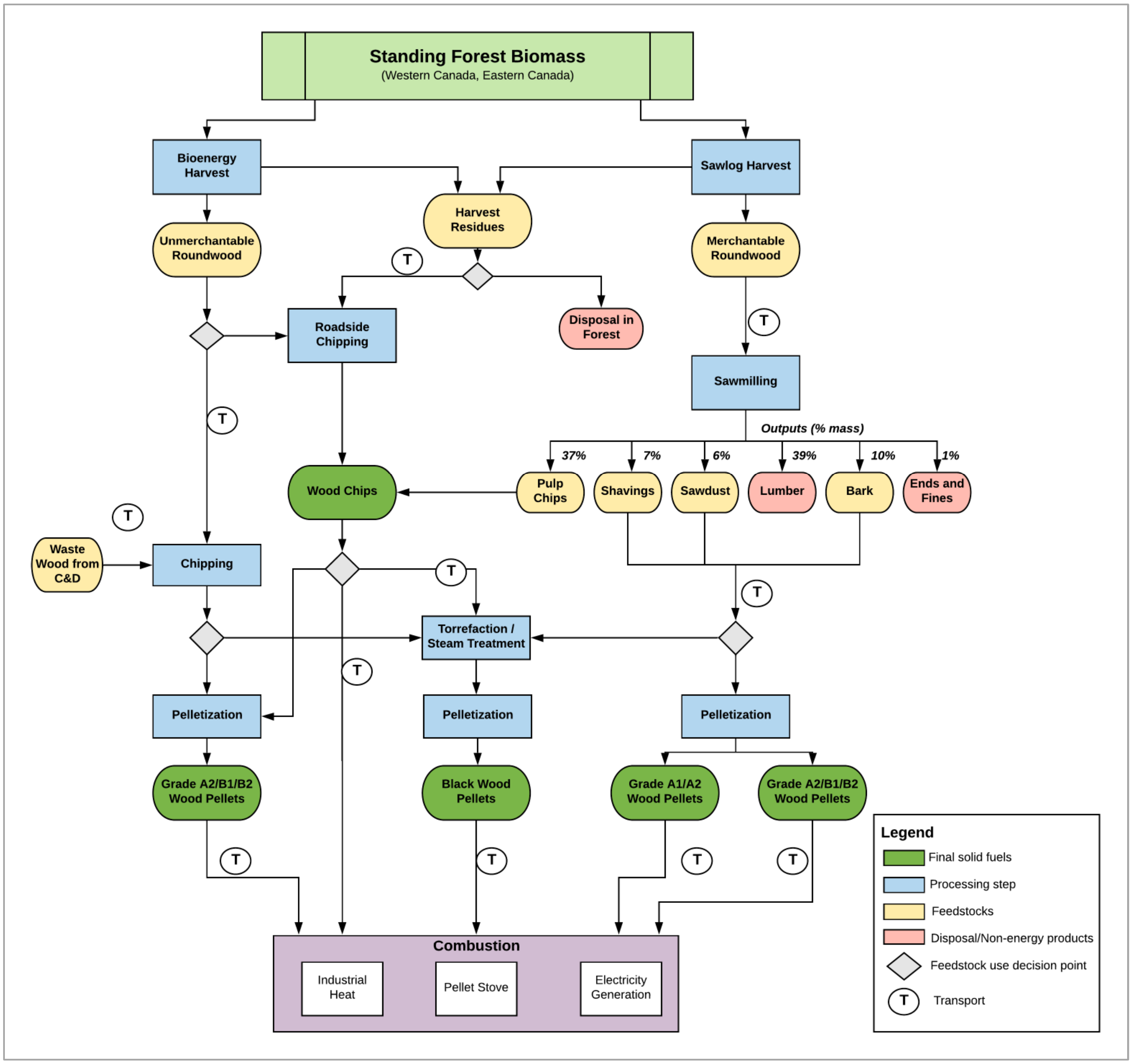

Figure 20. System boundaries and life cycle activities for solid fuels derived from wood biomass feedstocks, from extraction to combustion. Note that "Bioenergy Harvest" refers to incremental harvesting of standing forest biomass above and beyond the business as usual commercial harvesting.

Wood chips are also derived from multiple sources in the forest sector supply chain, ranging from roadside chipping of harvest residues to chipping of waste wood from C&D. The following sections provide an overview of the wood biomass feedstocks that were modelled for the Fuel LCA Modelling Tool.

Forest Harvest Residues (Bush Residual)

Forest harvest residues are comprised of tree stems, tops, and branches that are left after commercial harvest for merchantable roundwood. The management of these residues may vary from region to region in Canada depending on provincial forest management practices and also on the chosen harvest methods (e.g. cut-to-length, tree length, whole tree). Forest management plans and certification schemes typically require foresters to leave harvest residues on-site to support ecological functions (Roach & Berch, 2014). In other provinces, forest harvest residues are typically brought to the forest roadside to be either stockpiled or burned. When not left in the forest, these harvest residues can potentially be used for a number of low carbon fuel applications, such as being processed into wood chips for direct use, being chipped and used in wood pellet production, or for further fuel conversion such as pyrolysis; however, at present, this residues are rarely used for such applications in Canada.

The quantity of recoverable forest harvest residues varies by forest harvest technique. For example, in a study on Ontario forest harvesting for bioenergy it was indicated that recoverable residues ranged from up to 40% of merchantable volume for clear cuts, 20% of merchantable volume for shelterwood and thinning, and 0% for selection harvesting (McKechnie J. , 2012). These differences in recoverable residues are due primarily to the decision to harvest either the whole tree or to cut-to-length. Forest harvest techniques also vary from province to province; however, approximately 85% of forest harvesting in Canada is done by clearcutting (Statistics Canada, 2018).

After primary harvest, forest harvest residues are hauled to the roadside and chipped in roadside biomass processors prior to delivery to final use or for further bioenergy processing. In the context of solid fuels, wood chips produced from forest harvest residues may be used directly in energy applications or processed further into wood pellets or black pellets prior to use of a fuel. The life cycle activities associated with forest harvest residues therefore include the hauling of residues to the forest roadside, roadside chipping, and transport of wood chips to the producer or end user. At present the majority of these residues are left in the forest to decay and are considered a waste product. As such, the GHG emissions associated with primary forest harvesting are attributed to the primary forest products that are harvested. This modelling decision has been applied consistently in a number of LCAs of wood biomass energy (McKechnie J. , 2012) (Smyth, Kurz, Rampley, Lempriere, & Schwab, 2017) (McKechnie, Colombo, Chen, Mabee, & Maclean, 2011)

Sawmill Residues (Mill residues and hog fuel)

The production of lumber from Canadian sawmills results in a number of co-products from the sawing and planing of merchantable roundwood. These co-products, or residues, include parts of the roundwood that are sawn or planed to produce lumber, such as wood chips, sawdust, planer shavings, and various other wood ends and fines. The use of these residues varies considerably depending on the location and management practices of each sawmill. Some sawmill residues are used for onsite energy generation, some are transferred or sold to various users for energy applications and other product manufacturing (e.g. pulp and paper, animal bedding, etc.), and some are stockpiled or disposed of (Athena Sustainable Materials Institute, 2018a).

Harvesting of Merchantable Roundwood

The system boundary for sawmilling begins with primary harvest of merchantable roundwood in Canadian forests. This includes a number of activities, including forest thinning, fertilization, seedling growth, and replanting of logged forests. It also includes harvesting (e.g. feller buncher), delimbing, cutting, and hauling of roundwood from the forest to roadside, and from the roadside to the sawmill (Athena Sustainable Materials Institute, 2018a).

Sawmilling

Once delivered to the sawmill, merchantable softwood logs go through a process of sawing, kiln drying, and planing to produce lumber. The various sawmill residues are produced at different points in the process, as summarized in Table 92 below.

Table 92. Breakdown of the production of sawmill residues according to sawmill activity, by percent (Athena Sustainabile Materials Institute, 2012)

Residue	Sawing	Planing
Bark	100%	
Planer shavings		100%
Sawdust	97%	3%
Pulp chips	93%	7%
Trim ends		100%
Chipper fines	100%	
Wood waste (hog fuel)		100%

As noted, the disposition of sawmill residues will vary from operation to operation. In a 2012 study of the Canadian softwood lumber industry, the Athena Institute estimated the fate of different residue types according to end use (Table 93).

Table 93. Fate of sawmill residues for an average Canadian sawmill in 2012, shown as percent of total volume of residues produced (Athena Sustainabile Materials Institute, 2012).

Residue	Transferred*	Sold	Landfilled	Hog fuel	Stockpiled
Bark	21%	64%	3%	12%	1%
Planer shavings		71%		28%	1%
Sawdust		79%		21%	
Pulp chips	7%	93%			
Trim ends	7%	93%			
Chipper fines				100%	
Wood waste**	42%		58%		

**Transferred co-products are provided to other end users at no cost, as opposed to being sold to other end users.*

***Wood wastes are produced entirely during planing and are primarily landfilled and not used for other purposes*

The results of the analysis of residue use by the Athena Institute indicate that sawmill residues are almost fully utilized when considering their use onsite (hog fuel) and their use by other producers, with very little being stockpiled or landfilled.

Unmerchantable Roundwood

In addition to forest harvest and sawmill residues, another wood biomass feedstock option is the harvesting of roundwood from unmerchantable trees. Unmerchantable trees are those that are not suitable for timber or pulp for various reasons, including poor timber or fibre properties, they are diseased or deformed, or they are too small in diameter for sawmilling (Natural Resources Canada, 2018). In some instances, these trees are cut down and left on the forest floor in order to clear the way for harvesting of merchantable tree stands, while in other instances they are left standing. These unmerchantable trees are of increasing interest for bioenergy applications (International Energy Agency, 2019).

After harvest and hauling to the roadside, unmerchantable trees may be chipped at the roadside to produce wood chips for various applications or may be sent to wood pellet plants and debarked and/or chipped for production of white or black wood pellets. Unmerchantable trees may also be sent directly from harvest to CHP plants where they are chipped and combusted along with other wood biomass feedstocks.

Construction and Demolition Waste

Wood found in C&D waste could be another source of wood biomass feedstock for solid low carbon fuels; however, one of the barriers to use of this feedstock is the need for “clean” wood, i.e. wood that has not been chemically-treated or combined with other materials (i.e. plastics) in composite materials.

The use of C&D waste wood requires the collection and chipping of the wood and delivery of the wood to wood pellets plants or direct use of wood chips in heating applications.

Wood Biomass Fuel Conversion

The conversion of wood biomass feedstocks into final solid fuels takes various forms depending on the application and desired end use. In some instances, wood biomass feedstocks undergo a limited amount of sizing and/or drying, while in other instances they require more intensive processing. Process descriptions for the four solid low carbon fuels derived from wood biomass feedstocks are provided in the following sections.

Wood Chips

Wood chips are widely used as a solid fuel primarily for space heating or drying, as they are a locally available fuel that requires minimal processing (Natural Resources Canada, 2017a). Wood chips are typically produced during sawmilling operations, or from roadside chipping operations after forest harvest. Roadside chippers take numerous forms, including stationary and mobile units, and a range of size, power, and size reduction features (AEBIOM, 2008). In general, the production of wood chips involves the grinding or chipping of the wood followed by screening and air drying (Natural Resources Canada, 2017a).

Wood chips may be used directly for heating or drying energy or used as feedstock to produce brown or black wood pellets. The Canadian Standards Association (CSA) differentiate between Grade A (A1 and A2) and Grade B (B1 and B2) wood chips based on their source and properties such as ash and moisture content (Natural Resources Canada, 2017a). In general, Grade A wood chips derived from stem wood and milling processes are used for institutional space heating (e.g. schools, commercial buildings) while Grade B wood chips derived from chemically treated by-products and chemically untreated used wood are used for heavier industrial applications (e.g. pulp mills, district energy systems).

Based on the CSA classification, wood chips have a high heating value (HHV) of 10-11 MJ/kg and a density of 300-400 kg/m^3 (Natural Resources Canada, 2017b). This HHV is assumed to be for wood chips with a relatively high moisture content of 40-50%. Moisture content is the most important factor affecting calorific value for solid fuels, and the HHV and LHV for a given fuel will vary within a particular range depending on moisture content Figure 21.

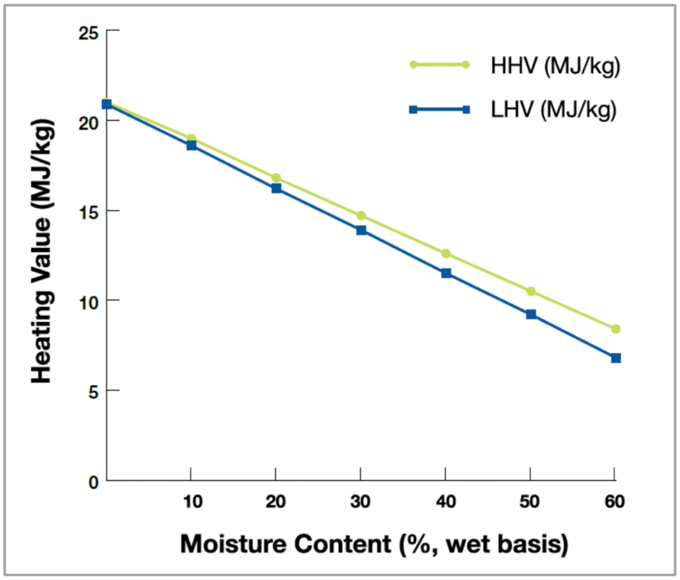

Figure 21. Relationship between HHV and LHV and moisture content for solid wood fuels (Natural Resources Canada, 2017b).

The moisture content for wood chips varies depending on the source and the level of drying that has been applied. Grade A1 wood chips have a moisture content of 10-25%, Grade A2 have a moisture content of generally 35% or lower, and Grade B wood chips generally have a moisture content of 35% or higher.

Wood Pellets

Wood pellets are a densified biomass fuel produced primarily from residues of traditional forestry operations such as sawmills and finished wood products manufacturing (Natural Resources Canada, 2017c). Forest harvest residues are also used, but to a lesser extent because they may contain higher amounts of bark and ash. Wood pellets are typically used for residential and institutional space heating, district heating plants, and electricity generation plants as a substitute for coal (Natural Resources Canada, 2017c).

According to the CAN/ISO-ISO 17225 solid biofuels standards, wood pellets are classified based on their source and properties, including Grade A (A1 and A2) and Grade B (B1 and B2). In general, Grade A1 and A2 wood pellets are used for residential or commercial heating applications and primarily come from mill residues (i.e. sawdust, shavings, and cut-offs) and stem wood. Grade A2 pellets can contain some logging residues and whole trees without roots. Grade B pellets are made from more diverse sources, and can include bark, residues from thinning and pruning, and chemically untreated used wood. The CSA also classifies industrial pellets (I1, I2, and I3) which are pellets used for more industrial uses such as electricity generation. Some key specifications for Grade A and Grade B wood pellets are summarized in Table 94.

Table 94. Properties of Grade A1, A2, and B wood pellets, as per the CAN/CSA-ISO 17225 Part 2 Standard (Natural Resources Canada, 2017c).

Property Class	Unit	Grade A1	Grade A2	Grade B
Moisture	% of weight	$\leq$ 10	$\leq$ 10	$\leq$ 10
Ash	% of weight	$\leq$ 0.7	$\leq$ 1.2	$\leq$ 2.0
Fines	% of weight	$\leq$ 1.0	$\leq$ 1.0	$\leq$ 1.0
HHV	MJ/kg	$\geq$ 18.6	$\geq$ 18.6	$\geq$ 18.6
Bulk density	kg/m^3	600 - 750	600 - 750	600 - 750

Aside from specific industry classifications, wood pellets also tend to be grouped according to their feedstock type and production process using terms like white pellets, brown pellets, and black pellets. A search through the literature and industry reports suggests that while the differentiation of black pellets is clear, there is a fair bit of inconsistency in the use of other terms such as “white” and “brown” to describe wood pellets. For the purposes of the Fuel LCA Modelling Tool, the following will be used:

- **Wood Pellets** – Grade A1/A2 and B1/B2 pellets made from any wood biomass source (i.e. harvested biomass, residues) produced through standard pelletization processes;
- **Thermally-treated Wood Pellets (black)** – pellets made from wood biomass of any source (i.e. harvested biomass, residues) that are thermochemically treated by either stream treatment or torrefaction prior to pelletization.

The different pathways for each type of pellet are shown in Figure 20.

Black wood pellets are considered advanced wood pellets, and as of the end of 2016, there was no commercial scale production of black wood pellets in Canada (Bradburn & Lakhdari, 2017). In contrast to standard wood pellets, black pellets include a thermal treatment step which decreases the moisture content and leads to a product with physical and chemical characteristic more similar to coal. This process makes the pellets more durable and gives them a higher energy density making them easier to use in coal-fired generating stations (Bradburn & Lakhdari, 2017).

Wood Biomass Fuel Combustion

Solid wood biomass fuels are used in a wide variety of applications and combusted in a large number of different combustion devices depending on the application. The emissions from combustion of solid wood biomass fuels will vary substantially depending on the type of combustion device. It is not feasible to capture the full range of possible combustion scenarios for each of the solid wood biomass fuels in the Fuel LCA Modelling Tool. The combustion of wood biomass solid fuels will be modelled for three general applications, including industrial combustion of wood chips in stoves, furnaces, and boilers, combustion of wood pellets in residential pellet stoves, and combustion of black pellets in large-scale electricity generation.

10.1.2 Crop Residue Fuels

Renewable solid fuel feedstocks are also produced within the agricultural sector, primarily from agricultural crop residues such as corn stover or wheat straw. Similar to wood residues, agricultural residues can be converted to energy-dense pellets and used for on-farm drying energy or sold to other end users; however, agricultural feedstocks contain silica, chlorine, and ash that cause serious problems during combustion. These feedstocks could be blended with wood and used in combustion, pyrolysis, or gasification.

For example, perennial grasses such as switchgrass or miscanthus can be combined with woody biomass and compressed into a pellet. Agricultural crop residues such as corn stover or wheat straw can also be used in this manner. If not blended, then solid fuels from agricultural residues require additional pretreatment.

Currently there is almost no commercial production of corn stover pellets or agri-wood pellets and very little information available on their production. In anticipation that solid fuels from perennials or crop residues may become more important in the development of low carbon fuels, a default pathway is included for pellets derived from corn stover.

Crop Residue Feedstocks

Corn stover is a waste product of corn cultivation. Corn stover refers to all of the above-ground parts of the corn plant except grain (i.e. stalks, leaves, and cobs). Approximately equal masses of stover and grain are produced during growth. In the United States, most corn stover is left on the fields, and about 5% of stover is removed for use in animal feeds and bedding ((Kim, Dale, & Jenkins, 2009). Farming practices vary from region to region, but it is assumed that Canadian practices are similar to those in the US in that most corn stover is currently left on corn fields after harvest and tilled into the soil over time.

Given that most crop residues are currently left on agricultural fields, these residues have been treated as a waste product in the Fuel LCA Modelling Tool and no upstream impacts from cultivation have been allocated to the residues. The removal of crop residues from agricultural fields requires additional energy for collection, and requires the input of additional nitrogen fertilizer to replace the lost nutrients from residue decay (Chen, et al., 2017).

Crop Residue Fuel Conversion

The conversion of corn stover into pellets requires the removal of corn stover from corn fields and processing in a densification plant. In general, this would require the removal, baling and transport of corn stover over a given distance to the densification plant. Because the stover contains nitrogen, which is being removed from the field, the field will require additional nitrogen (N) fertilizer the following year, which is included in the corn stover inventory (see Section 4.8.) The location of densification plants could vary depending on the scale of production, and smaller plants could be located closer to corn fields; however, there are no corn stover production facilities in Canada.

No information is available on corn stover densification processes in Canada. A 2012 publication by Li et al. describes an LCA of densifiying wheat straw pellets in the Canadian Prairies (Li X. , Mupondwa, Panigrahi, Tabil, & Adapa, 2012), and it is assumed that the densification process would be similar for corn stover, and in many ways similar to wood pellet production in overall process. The densification process generally includes a series of steps including receiving bales of residues, grinding, pelletizing, cooling, and screening. In addition, a recent publication on production of corn stover pellets in Idaho, US indicated that a corn starch binder may also be required to strengthen the densification of the corn stover (Tumuluru, Conner, & Hoover, 2016).

Crop Residue Fuel Combustion

Given the non-existent use of pellets made from corn stover in Canada, the default pathway in the Fuel LCA Modelling Tool will include combustion of corn stover pellets for heating. Future additions to the tool may include electricity generation should this pathway develop.

10.2 Modelling Approach for Solid Low Carbon Fuels

The following sections provide a brief overview of the modelling approach for low carbon solid fuels, as well as discussion of some key methodological issues to be addressed in the modelling.

10.2.1 Development of Unit Process Building Blocks

The overall modelling approach for Milestone 3 is to develop unit processes to serve as building blocks for current and future modelling work in the Fuel LCA Modelling Tool. In the case of solid low carbon fuels this approach is particularly relevant since there are a variety of fuel feedstocks that may be used in any fuel conversion process, and these are all based on a basic set of feedstocks that are produced within the Canadian forestry supply chain (or in the case of corn stover pellets, from the Canadian agricultural industry).

The key building blocks for wood biomass solid fuels are forest harvesting and sawmilling activities, from which multiple feedstocks are produced, including unmerchantable roundwood, forest harvest residues, wood chips, and various other sawmill residues (e.g. sawdust, planer shavings) (see Figure 19). With these building blocks in place, with regional variation reflected in their production where possible (e.g. differences in fuel consumption, differences in electricity grids, etc.), users of the Fuel LCA Modelling Tool that want to build a wood pellet process can choose the appropriate feedstock(s) from the available building blocks and pull them in to their specific pellet production pathway. They can also copy and modify these building blocks with their own more recent or process-specific data.

Using this building blocks approach, even in cases where only literature data is available, or where no data is available, unit processes can still be developed and included as defaults in the Fuel LCA Modelling Tool and be updated by tool users when data is available.

The modelling work in Milestone 3 also relies heavily on fossil fuel unit processes that were developed in Milestone 2, including fuel inputs to machinery and equipment (e.g. diesel, natural gas, etc.) and transportation processes (e.g. trucks, rail, pipelines). These unit processes will be pulled from the ECCC Fuels database and incorporated into the low carbon fuel pathway models where needed.

10.2.2 Regional Variation

There are some regional variations for solid low carbon fuels which could influence carbon intensity. These include fuel consumption in forest harvesting, fuel consumption in sawmilling and other processing activities, inputs and crop management practices for corn production (i.e. corn stover) and background energy systems such as variations in electricity grids providing energy to fuel conversion processes. The sourcing of regional/provincial feedstocks could also influence transport distances and modes for feedstock delivery and final fuel delivery.

These differences are reflected in the modelling as much as possible within the confines of the available data. For example, forest harvesting data is available only for Western and Eastern Canada[15], and not a provincial level. As such, tool users will need to choose a unit process from either of these two regions, or choose the unit process for Canadian average harvesting, and would not be able to choose provincially specific harvesting data in this version of the Fuel LCA Modelling Tool. With respect to background energy systems, electricity grid carbon intensities are available at a provincial level based on work completed in Milestone 2, as are some fuels (e.g. diesel), and will be incorporated into the unit processes available for modelling solid low carbon fuels. For example, modelling the production of wood pellets in British Columbia could include the use of British Columbia electricity to power the pelletization process.

10.2.3 Co-Product Allocation

Co-products from sawmilling operations, including sawdust, bark, and planer shavings, are a widely-used input for low carbon solid fuels. In modelling these feedstocks, there is a need to allocate the impacts of sawmilling across the various co-products. In Milestone 1 and 2 it was established through discussions with ECCC that the upstream carbon intensity of a process would be allocated to its co-products according to energy content. Effort has been made to use this approach consistently in modelling work for Milestone 3; however, using the building blocks approach for the Fuel LCA Modelling Tool, the capability to choose different allocation approaches will be incorporated in the tool. For sawmilling, allocation of upstream impacts to lumber and sawmilling co-products is often done by mass in the literature (Athena Sustainable Materials Institute, 2018a), and represents a more appropriate way of allocating for solid low carbon fuel feedstocks since sawmilling co-products are often valued for physical properties other than their energy content. The LCI data provided for Canadian sawmilling included a subdivision of material and energy inputs and material outputs expressed relative to each of the three phases of sawmilling (sawing, drying, and planing). These data allowed us to subdivide the impacts of the sawmilling process to each of the material outputs based on the percentage of each activity that is attributed to each co-product. For example, as shown in Table 97, 100% of the bark is produced from sawing, and 70% of the electricity consumption is attributed to sawing. As such, none of the impacts associated with drying and planing were attributed to bark since it is only produced during sawing. Other co-products from sawing included sawdust (97%), pulp chips (93%), and chipper fines (100%). Using these data, the 70% of total electricity used for sawing was then allocated to each of these co-products of sawing based on their relative masses. After the limits of subdividing the system were reached, mass allocation was used to finalize the attribution of impacts to each co-product. These calculations are summarized in the unit process data sheets for sawmilling which are provided as a separate appendix to the final report.

10.2.4 Biogenic Carbon

In remaining consistent with the Government of Canada’s policy on biogenic carbon, as shown in Canada’s National Inventory Report (Government of Canada, 2018), emissions

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[15] The Athena study included survey data from sawmills in British Columbia (7), Alberta (2), Ontario (7), Quebec (6), and New Brunswick (1). “Western” refers to mills in British Columbia and Alberta, while Eastern refers to mills in Ontario, Quebec, and New Brunswick.

of biogenic carbon from combustion of solid low carbon fuels are not included in the carbon intensity calculations. Biogenic carbon emissions are calculated and reported separately from the default carbon intensity values.

Carbon emissions associated with direct land use change will be included in instances where feedstock production requires the conversion of land from existing use to bioenergy production. Indirect land use change is excluded from the carbon intensity calculations.

10.3 Life Cycle Inventory for Solid Low Carbon Fuels

10.3.1 Solid Wood Biomass Fuels

Forest Harvesting

Merchantable Roundwood

The best publicly available LCI data for primary Canadian forest harvesting operations for merchantable roundwood is from the Athena Sustainable Materials Institute, who have completed a number of LCAs of Canadian forest products. In their most recent publications on Canadian softwood lumber manufacturing, they provide fuel consumption for production-weighted Canadian average softwood harvesting based on surveys of 11 forest harvesting operators for 2015, and production-weighted Eastern Canadian average softwood harvesting based on 5 forest harvesting operators for 2015. These data are summarized in Table 95 and represent primarily mechanical logging (96-100%) of Canadian softwoods.

Table 95. Stump to roadside fuel consumption for average Canadian and average Eastern Canadian primary softwood harvesting in 2015, expressed relative to harvesting of 1 m^3 of softwood (Athena Sustainable Materials Institute, 2018a).

Input	Unit	Amount	Unit	Amount
	Canada		Eastern Canada	
Silviculture & Land Use*				
Seedlings planted	number/m^3	3.5	number/m^3	3.2
Aerial seeding	mg/m^3	92	mg/m^3	83
Area harvested	ha/m^3	0.0052	ha/m^3	0.0066
Energy Use by Fuel Type				
Diesel	l/m^3	2.17	l/m^3	3.06
Gasoline	l/m^3	0.16	l/m^3	0.18
Propane	l/m^3	0.01	l/m^3	0.01

**Data on silviculture and land use parameters are provided as context to the harvesting data. The Athena LCA models do not account for GHG emissions associated with seeding and planting.*

One of the objectives for the Fuel LCA Modelling Tool is to be able to reflect regional or provincial differences in carbon intensity for low carbon fuels. Unfortunately, the Athena Institute's most recent studies do not provide any LCI data for Western harvesting; however, in the 2012 version of this same report, in addition to the Canadian average, a breakdown of Western and Eastern forest harvesting data was provided. These data are summarized in Table 96 and are based on surveys of 15 producers for the 2006-2007 production year and represent predominantly mechanical harvesting (94-97%).

Table 96. Stump to roadside fuel consumption for Canadian primary softwood harvesting in 2006-2007, broken down by Eastern and Western Canada, expressed relative to harvesting of 1 m^3 of softwood (Athena Sustainabile Materials Institute, 2012).

Input	Unit	Amount	Unit	Amount	Unit	Amount
	Eastern Canada		Western Canada		Canada	
Silviculture & Land Use						
Seedlings planted	number/m^3	3.9	number/m^3	3.1	number/m^3	3.5
Aerial seeding	mg/m^3	82	mg/m^3	37.8	mg/m^3	92
Area harvested	ha/m^3	0.0066	ha/m^3	0.0036	ha/m^3	0.0052
Rotation age at harvest	years	87	years	102	years	94
Energy Use by Fuel Type						
Diesel	l/m^3	3.29	l/m^3	2.26	l/m^3	2.84
Propane	l/m^3	0	l/m^3	0.0013	l/m^3	0.0006
Electricity	kWh/m^3	0.0296	kWh/m^3	0.0296	kWh/m^3	0.0296

In comparing the harvesting LCI data from both Athena Institute reports, Canadian average and Eastern Canadian average diesel consumption decline by 24% and 7%, respectively. Propane consumption increases by over 150%, and gasoline use is reported instead of electricity consumption. In the interest of using the most recent LCI data while also being able to reflect regional differences in harvesting, we will use the 2012 regional breakdown to scale the diesel, propane, and gasoline combustion amounts for Western Canada. In the 2012 data, diesel consumption in Western Canada was 20% lower than the Canadian average.

Unmerchantable Roundwood

The forest harvest LCI data from the Athena Institute is for primary forest harvest for merchantable saw logs. This type of harvesting is done primarily by clear cutting (Statistics Canada, 2018). Unmerchantable trees may be harvested as part of a clear cut and brought to the forest roadside, or they may be harvested during more selective cutting operations such as thinning. The Fuel LCA Modelling Tool will include two alternative forest harvest unit processes to reflect the fact that unmerchantable roundwood may be extracted from the forest in different ways, including:

- Harvesting of unmerchantable trees by thinning operations and skidding to the forest roadside; and
- Skidding of previously harvested unmerchantable trees to the roadside.

Canadian-specific data were not available for these operations; however, in a 2012 LCA study of Southeast United States wood biomass collection and processing, the Consortium for Research on Renewable Industrial Materials (CORRIM) provided LCI data for thinning, skidding, and chipping of forest thinnings (Johnson, Lippke, & Oneil, 2012). These data will be used as the default values for fuel consumption for harvesting and skidding of unmerchantable trees in Canada:

- Felling (large biomass feller buncher) – 0.81 l of diesel/oven dry tonne
- Skidding (large biomass skidder) – 2.64 l of diesel/oven dry tonne

Users of the Fuel LCA Modelling Tool will be able to modify the fuel consumption amounts for these activities to reflect different technologies or different practices in the future.

Wood Chipping

The chipping of harvest residues and unmerchantable roundwood at the forest roadside can be done using a wide range of technologies with varying capabilities and fuel consumption. The unit process for roadside chipping of wood biomass is based on an average value for fuel consumption per amount of wood chipped from the literature. When using the Fuel LCA Modelling Tool, users will be able to modify the fuel consumption rate for the chipper if they have primary data or more appropriate literature data to use.

The default fuel consumption value for roadside chipping of forest harvest residues, including chipping and loading, is 4.3 litres of diesel per oven dry tonne of biomass processed. This value is from a study of wood biomass energy in Ontario from 2012 (McKechnie J. , 2012). The default fuel consumption value for roadside chipping of whole trees is assumed to be the same as chipping of harvest residues.

Sawmilling

The most recent publicly available LCI data for Canadian sawmilling operations is from LCAs carried out by the Athena Sustainable Materials Institute. In 2018 they published LCI data based on surveys of 23 Canadian sawmills. These data include material and energy inputs and an average product and co-product slate, and were also broken down to provide both a Canadian average (Athena Sustainable Materials Institute, 2018a) and Eastern Canadian average (Athena Sustainable Materials Institute, 2018b). The LCI data for production of lumber in Canadian sawmills is summarized in Table 97, including a subdivision of material and energy inputs and material outputs relative to each phase of the sawmilling process (sawing, drying, planing). These data were used to sub-divide the sawmill activities relative to the various co-products and reduce the amount of co-product allocation required.

Table 97. Life cycle inventory for the inputs and outputs of average Canadian and average Eastern Canadian sawmilling to produce softwood lumber in 2015, expressed per m^3 of lumber produced.

Material or Fuel	Units	Amount per m^3 of lumber	Units	Amount per m^3 of lumber	Sawing	Kiln Drying	Planing
	Canada		Eastern Canada		Canada		
Inputs							
Roundwood	kg (dry)	1,097	kg (dry)	1,111			
Hydraulic fluids	l	0.13	l	0.15	73%	5%	22%
Motor oils	l	0.29	l	0.22	67%	7%	26%
Greases	kg	0.01	kg	0.01	69%	8%	24%
Electricity	kWh	71.89	kWh	70.9	70%	9%	21%
LPG	l	0.18	l	0.28	39%	17%	44%
Gasoline	l	0.06	l	0.03	61%	11%	28%
Diesel	l	2.06	l	2.15	62%	11%	27%
Heating oil	l	0.46	l	0.92		100%	
Natural gas	m^3	4.67	m^3	0.8	16%	73%	11%
Hog fuel	kg (dry)	79.36	kg (dry)	106.18		100%	
Outputs							
Softwood lumber	kg	428	kg	408			
Bark	kg	105	kg	110	100%		
Planer shavings	kg	74	kg	78			100%
Sawdust	kg	66	kg	69	97%		3%
Pulp chips	kg	406	kg	426	93%		7%

Trim ends	kg	7	kg	7			100%
Chipper fines	kg	2	kg	2			
Wood waste	kg	9	kg	9	100%		

Unfortunately, data for sawmilling operations in Western Canada were not provided in the Athena Institute LCAs. For the default values in the Fuel LCA Modelling Tool, the use of sawmill residues from Western Canadian sawmills will use the Canadian average until more regionally specific data can be provided.

10.3.2 Pelletization

Within the pellet plants currently operating in Canada, there is a fair amount of variability in energy consumption and emissions associated with pelletization as a result of the use of different feedstocks and the production of different grades of wood pellets. As a result, individual pellet producers will be able to modify the unit process for pelletization in the Fuel LCA Modelling Tool to reflect their specific operations. For the default pelletization process, LCI data on wood pellet production in Ontario was obtained from a recent publication (McKechnie, Saville, & MacLean, Steam-treated wood pellets: Environmental and financial implications relative to fossil fuels and conventional pellets for electricity generation, 2016). The LCI data are summarized in Table 98.

Table 98. Energy inputs to pelletization, expressed per oven dry tonne of graded pellets produced in Ontario.

Input	Unit	Amount
Debarking and grinding - Electricity	kWh/dry tonne	3.75
Pellet production – Electricity	kWh/dry tonne	144
Pellet production – thermal energy	GJ/dry tonne	3.0
Wood pellet energy content	GJ/dry tonne	19

In another recent study of wood pellet production in Canada, Padilla-Rivera et al. used LCA to quantify the environmental impacts of wood pellet production by two different production plants in Québec. The LCI data from this study of 2014 production showed electricity consumption values that were both higher (163 kWh/tonne of pellets) and lower (93.7 kWh/tonne of pellets) than what is used by McKechnie et al. (2016), and also shows much higher thermal energy use by one producer, including use of diesel (3.22 MJ/tonne of pellets) and natural gas (1,400 MJ/tonne of pellets) (Padilla-Reivera, Barrette, Blanchet, & Thiffault, 2017). These values reflect the types of variation that may be observed in wood pellet production LCI data. This variation will be captured in the uncertainty analysis but may also be addressed by the addition of more specific data from low carbon fuel producers using the Fuel LCA Modelling Tool in the future.

Thermal Treatment

Thermal treatment of wood pellets is an emerging part of the wood pellets sector with no current commercial scale production in Canada. In developing default carbon intensity values for black wood pellets, we used the best available literature values to characterize the production of both steam-treated and torrefied wood pellets.

Steam-Treated Wood Pellets

A recent Canadian study quantified the life cycle environmental impacts of white pellets and black wood pellets produced in Ontario for use in electricity generation. The data for black pellet production are based on a demonstration-scale plant in Norway, and were used to develop the default pathway for black pellets produced using steam-treated biomass. The energy inputs to production of steam-treated wood pellets are summarized in Table 99.

Table 99. Energy inputs to the production of black wood pellets using stream-treated biomass in Ontario in 2014 (McKechnie, Saville, & MacLean, Steam-treated wood pellets: Environmental and financial implications relative to fossil fuels and conventional pellets for electricity generation, 2016).

Input	Unit	Amount
Debarking and grinding - Electricity	kWh/dry tonne	3.75
Pellet production – Electricity	kWh/dry tonne	120
Pellet production – thermal energy	GJ/dry tonne	3.8
Energy content	GJ/dry tonne	21

It is noted that the energy content of the thermal treated pellets is 21 GJ/dry tonne, which is 2 GJ higher than conventional pellets that were modeled in the same study (see Table 98). This difference is reflected in the model of wood pellet combustion for black pellets. LCI data for the upstream production of wood biomass feedstocks for black pellets are based on the modelling from Milestone 3.

Torrefied Wood Pellets

Black pellets can also be produced through a torrefaction process. Torrefaction is a form of pyrolysis that results in partial thermal decomposition in the absence of oxygen. It is conducted between 200 and 300 degree Celsius to remove volatiles from the wood prior to densification (Adams, Shirley, & McManus, 2015).

There are currently no commercial scale torrefied wood pellet plants operating in Canada, and no LCI data available for Canadian production of torrefied wood pellets. To model the default carbon intensity of black wood pellets from torrefaction, we used LCI data from a 2015 study on torrefied wood pellet production in Europe (Adams, Shirley, & McManus, 2015). This study compared the life cycle impacts of both torrefied wood pellets and conventional wood pellets. The LCI data from this study are summarized in Table 100.

Table 100. Life cycle inventory data for the production of torrefied black wood pellets and conventional graded pellets from chipped roundwood in Europe (Adams, Shirley, & McManus, 2015).

Input	Torrefied Black Pellets		White Pellets	
	Unit	Amount	Unit	Amount
Process heat*	MJ/tonne	4,000	MJ/tonne	1,560
Natural gas	m^3/tonne	14.5	m^3/tonne	36.7
Grinding – Electricity	kWh/tonne	77	kWh/tonne	260
Pelleting - Electricity	kWh/tonne	150	kWh/tonne	50
Bulk density	kg/m^3	800	kg/m^3	650
LHV	MJ/kg	22.0	MJ/kg	15.5
Moisture content	%	5	%	10

**Process heat is assumed to be provided by recirculated torrefaction gas. In some configurations this may be supplied by burning biomass or fossil fuels.*

Similar to thermal treated pellets, the energy content of torrefied pellets was shown to be higher than conventional pellets, along with higher bulk density and lower moisture content. These differences are reflected in the model of wood pellet combustion for black pellets. The HHV and carbon content of torrefied wood pellets can vary depending on the torrefaction conditions, but 21.5 – 22 MJ/kg is generally considered to be representative of average torrefied pellets (McNamee, et al., 2016). LCI data for the upstream production of wood biomass feedstocks for black pellets are based on the other solid low carbon fuel models from Milestone 3.

Feedstock and Fuel Transport

An important consideration for feedstock and final solid fuel transport is the moisture content, as many of the wood biomass feedstocks begin as “wet” materials with relatively high moisture content, such as chipped harvest residues, and then have much lower moisture content by the time they are processed into final fuels. For example, while sawdust from a sawmill may be shipped to a pellet mill at 30-40% moisture content, the final pellets shipped to the end user will likely have a moisture content of 5% or less. As such, the feedstock transport must account for the additional fuel consumption to transport wet materials, while the final solid fuel transport must account for the lower moisture content in the final fuel.

The transportation of feedstocks and final solid fuels was assumed to be all by truck and rail. In modelling this transport, we used the truck and train unit processes that were created in Milestone 2 to capture the upstream and combustion emissions associated with these modes of transport. Further discussion of transportation modelling is provided in Appendix B.

Combustion

Emissions factors for combustion of solid wood biomass fuels are summarized in Table 101 for industrial heating, pellet stove heating, and electricity generation. It is noted that these emissions factors are based on generic assumptions about combustion efficiency and moisture content of the wood fuel that were developed and are used by the Government of Canada. Future users of the Fuel LCA Modelling Tool will be able to modify these emissions factors based on the measured or projected characteristics of particular wood fuels and combustion devices. The efficiency of the combustion device influences the amount of feedstock required to deliver a MJ of useful energy, which is the functional unit of this study. As such, a lower efficiency device would need to consume more feedstock to deliver a MJ of useful energy relative to a more efficiency device. Assumed efficiency rates for combustion devices are:

- Pellet stove – 80% (U.S. EPA, 2019)
- Industrial furnace – 90% (Ayer & Dias, 2018)
- Electricity generation – 26% (McKechnie J. , 2012)

The CO_2 emissions from combustion are considered as biogenic carbon since they are from wood biomass feedstock. As such, although these emissions will be quantified and reported separately, they will not be included in the default carbon intensity values for low carbon solid fuels.

Table 101. Combustion emissions factors for the modelled solid wood biomass fuel applications (Government of Canada, 2018).

Feedstock	Application	CO_2 (g/kg fuel)	CH_4 (g/kg fuel)	N_2O (g/kg fuel)
Wood Chips	Industrial Combustion	840	0.09	0.06
Wood Pellets	Pellet Stove	1,652	4.12	0.059
Wood Pellets and Black Wood Pellets	Electricity Generation	840	0.09	0.06

10.3.3 Solid Fuels from Crop Residues

Feedstock Production

Feedstock production for corn stover pellets is based on the collection and transport of corn stover from corn fields, and the replacement of nitrogen using additional fertilizer application to the corn fields from which residues were removed. This modelling step is described in Section 4.8. From the farm gate, LCI data for the baling and delivery of corn stover to the densification plant were derived from literature sources, including an LCA of densified wheat straw pellets (Li X. , Mupondwa, Panigrahi, Tabil, & Adapa, 2012). Transport of corn stover bales from the field to the densification plant were modeled by estimating average transport distance based on corn production locations and using unit processes for truck and rail transport developed in Milestone 2.

Feedstock Conversion

LCI data for Canadian corn stover densification is not available. Data are available in the literature on the densification of wheat straw from the Canadian Prairies and the energy consumption for densification was used as a proxy. It is noted in the wheat straw LCA that a range of energy use values have been reported for densification of agricultural residues, from a low of 30 kWh/tonne to a high of 106 kWh/tonne (Li X. , Mupondwa, Panigrahi, Tabil, & Adapa, 2012). The value used for wheat straw densification in the Canadian Prairies is 74.4 kWh/tonne, which sits approximately in the middle of this range and provides a reasonable default value for the Fuel LCA Modelling Tool. In a simulation study for corn stover pellet production in Idaho, energy consumption for densification of corn stover was estimated to be 118 – 126 kWh/tonne depending on moisture content, and approximately 75-94 kWh/tonne when a 2% corn starch binder was used to enhance densification (Tumuluru, Conner, & Hoover, 2016). In the Fuel LCA Modelling Tool, uncertainty analysis will be used to capture the influence of this range in energy consumption on the default carbon intensity for corn stover pellets.

Fuel Combustion

Specific combustion emissions factors for corn stover in Canada were not available in the Canada NIR documentation. As an alternative, combustion emissions factors for corn stover pellets are based on emissions data from the United States Environmental Protection Agency (United States Environmental Protection Agency, 2016), as summarized below in Table 102.

Table 102. Combustion emissions factors for corn stover pellets, expressed per MJ of pellets combusted (United States Environmental Protection Agency, 2016).

Feedstock	Energy Content (HHV) (MJ/kg)	CO_2 (g/MJ)	CH_4 (g/MJ)	N_2O (g/MJ)
Corn Stover	8.7	118	0.032	0.0042

The CO_2 emissions from combustion are considered as biogenic carbon since they are from agricultural feedstock. As such, although these emissions will be quantified and reported separately, they will not be included in the default carbon intensity values for low carbon solid fuels.

10.4 Carbon Intensity Results for Solid Low Carbon Fuels

CI results for solid low carbon fuels are summarized in Table 103 below. Results are shown for three different end use applications, including combustion in a pellet stove, combustion in an industrial furnace, and combustion for electricity generation, each with different average combustion efficiencies.

Table 103. Canadian average carbon intensity values for solid low carbon fuel pathways for three energy applications and a range of biomass feedstocks, expressed in g CO_2 eq./MJ.

Solid Low Carbon Fuel Pathway	Carbon Intensity (g CO_2 eq./MJ)
Pellet Stove	
Wood pellets, from sawdust {CA}	15
Wood pellets, from unmerchantable roundwood {CA}	15
Industrial Furnace	
Wood chips, from harvest residues {CA}	5.6
Wood chips, from unmerchantable roundwood {CA}	6.9
Pellets, from corn stover {CA}	23
Electricity Generation	
Wood pellets, from sawdust {CA}	21
Black wood pellets, from sawdust, steam-treated {CA}	18
Black wood pellets, from sawdust, torrefied {CA}	24
Wood pellets, from unmerchantable roundwood {CA}	17
Black wood pellets, from unmerchantable roundwood, steam-treated {CA}	15
Black wood pellets, from unmerchantable roundwood, torrefied {CA}	21

The CI values for each application reflect different combustion efficiencies and so should not be compared directly across end uses. For electricity generation, wood pellets produced from unmerchantable logs had the lowest CI values at 15 (steam-treated) and 17 g CO_2 eq. per MJ (standard pellets). Torrefied wood pellets made from sawdust, which have a slightly greater HHV than standard wood pellets, had the highest carbon intensity per MJ of all the electricity generation options. For the industrial furnace end use, densified pellets from corn stover had the highest CI at 23 g CO_2 eq. per MJ, which was significantly higher than both types of wood chips modelled.

The primary contributors to the CI of solid low carbon fuels are the feedstock production and pelletization steps (Table 104). For conventional wood pellets, the harvesting and sawmilling activities to produce sawdust account for 33% of the life cycle GHG emissions and pelletization accounts for 24%. For torrefied wood pellets, the increased energy requirements to treat the pellets is the most notable change in the contribution analysis relative to other pellets, with pelletization accounting for 46% of total GHG emissions. This is why the torrefied pellets have the highest impact despite their improved energy density relative to other pellets. Feedstock and wood pellet transport are also shown to account for a non-negligible share of the overall carbon intensity of these solid fuels.

Table 104. Contribution analysis for Canadian average electricity generation from three different types of wood pellet, expressed per life cycle stage in g CO_2 eq./MJ of energy produced.

Life Cycle Stage	Carbon Intensity (g CO_2 eq./MJ)		
	Wood Pellets	Steam-Treated	Torrefied
Harvesting – merchantable logs	4.3	3.5	3.6
Sawmilling – sawdust	2.7	2.4	2.3
Feedstock transport	2.1	1.9	1.8
Pelletization	5.3	4.0	11
Pellet transport	2.8	2.5	2.4
Combustion - electricity	3.8	3.4	3.2
Total	**21**	**18**	**24**

10.4.1 Uncertainty Analysis

Uncertainty analysis was conducted for Canadian average solid low carbon fuels using Monte Carlo analysis. Results of the uncertainty analysis are shown in the violin plots in Section 12 and discussed relative to the uncertainty of other low carbon fuels in that section. Below in Table 105 the key results of the uncertainty analysis from each of the six sources are summarized.

Overall the results for solid low carbon fuels show a relatively high level of uncertainty, with max values for most fuels being nearly double the baseline value, and min values for most fuels being nearly 40-50% of the baseline value.

Table 105. Results of uncertainty analyses for selected solid low carbon fuels. Results based on Monte Carlo analysis of 2,000 runs with a confidence interval of 95%.

Final CI	Mean	Median	SD	Min (2.5%)	Max (97.5%)
Wood pellets, from sawdust, for electricity generation {CA}					
20.9	21.5	20.3	7.03	11.6	39.6
Wood pellets, steam treated, from sawdust, for electricity generation {CA}					
18.2	18.5	17.2	6.24	10	34.5
Wood pellets, torrefied, from sawdust, for electricity generation {CA}					
24.2	24.8	23.3	7.93	13.7	43.9
Wood chips, from unmerchantable roundwood, industrial furnace {CA}					
6.9	7.12	6.59	2.61	3.8	13.4
Pellets, from corn stover, industrial furnace {CA}					
22.8	22.9	21.9	7.29	12.3	40.3
Wood pellets, from sawdust, residential stove {CA}					
14.8	15	14.6	2.49	11.1	20.5

10.5 Data Gaps and Limitations for Solid Low Carbon Fuels

The Canadian average CI values for solid low carbon fuels are based on Canadian average electricity inputs. Electricity is one of the primary energy inputs for conversion of solid low carbon feedstocks (i.e. pelletization, thermal treating, etc.) and as such, the CI results are quite sensitive to the background electricity grid. For example, wood pellets produced from sawdust in Alberta for residential pellet stoves would have a CI of 25 g CO_2 eq./MJ, which is 66% higher than the Canadian average. This is a result of the greater reliance on fossil fuels for electricity generation in Alberta. In addition, the CI value for wood pellets is highly sensitive to the source of drying energy. While it has been assumed that average Canadian facilities primarily use biomass or process heat for drying energy, some pellet plants may use natural gas or heating oil, and this could lead to significantly higher CI values. For example, the Canadian average CI value for wood pellets from sawmill residues with natural gas drying energy would be 29 g CO_2 eq. per MJ, which is over 90% higher. The literature on wood pellet production also indicates that pelletization energy can vary significantly from facility to facility depending on a number of factors, and this has a significant influence on the overall CI value.

The primary data gap for solid low carbon fuels is a lack of operating data for Canadian wood pellet plants. The collection of primary data on the inputs and outputs of operating Canadian wood pellet plants would provide key information to develop more representative CI values and to develop a full grasp on the variability of their operating inputs and outputs.

11. Pyrolysis Oils

11.1 System Boundaries and Technical Descriptions for Pyrolysis Oils

Pyrolysis is the thermal decomposition of carbon-rich mass occurring in the absence of oxygen and is the fundamental chemical reaction that is the precursor to both combustion and gasification processes. Pyrolysis generally produces bio oil, solid biochar, and non-condensable gases (NCG) which are typically rich in combustible hydrocarbons. Pyrolysis processes are classified as either slow pyrolysis or fast pyrolysis. Slow pyrolysis takes several hours to complete and generally results in biochar as the main product (Roy & Dias, 2017). Fast pyrolysis takes seconds to complete and results in a higher yield of bio oil (~60%) (Danish Energy Agency, 2017).

Pyrolysis oil is a dark-brown, free-flowing liquid that is generally referred to as bio oil. Bio oil has several different characteristics relative to conventional oil, including a higher water content and a lower sulfur content than conventional oil. Bio oil can be stored, pumped, and transported similar to petroleum products but has a higher pH and its corrosive nature means that modifications are required for storage and transportation (Bradburn, 2014).

At present there is very little commercial-scale production of pyrolysis oils in Canada; however, there is growing interest in using pyrolysis to convert wood residues to bio oil as a substitute for fossil fuels in industrial heating applications (Ayer & Dias, 2018). A recent survey of the global pyrolysis oil market indicated that although there were up to 73 separate pyrolysis technology ventures in Canada in 2014, the majority of these were start-ups with little potential (Canadian Biomass, 2014). At present, Ensyn's commercial pyrolysis production system in Ontario is the only known Canadian facility that has been consistently producing pyrolysis oil at a commercial scale over the long term.

The system boundaries for pyrolysis oil production are closely linked with the system boundaries and life cycle activities associated with solid wood biomass fuels. As shown in Figure 22, feedstock production for pyrolysis oil is assumed to come from the same wood biomass feedstock sources as solid low carbon fuels. A more complete description of the system boundaries and life cycle activities is provided in the following sections.

11.1.1 Feedstock Production

Pyrolysis technologies can handle a range of biomass feedstocks, including residues from agriculture, forest residues, energy crops, and municipal solid wastes (Roy & Dias, 2017). Essentially almost any form of organic material can be introduced into a pyrolyzer; however, because the chemical properties of the feedstock have a significant influence on both the product yields and quality (Laird, Brown, Amonette, & Lehmann, 2009), the feedstocks used for pyrolysis oil production are carefully selected.

For the purposes of establishing building blocks and default carbon intensities for pyrolysis oil in the Fuel LCA Modelling Tool, the feedstocks available for the pyrolysis oils pathway will be derived from the wood biomass feedstocks described in Section 10.3.1 of the solid low carbon fuel summary (e.g. harvest residues, sawmill residues, unmerchantable roundwood). In the future this could be expanded to include agricultural residues once more data on pyrolysis of agricultural residues is available or provided by producers.

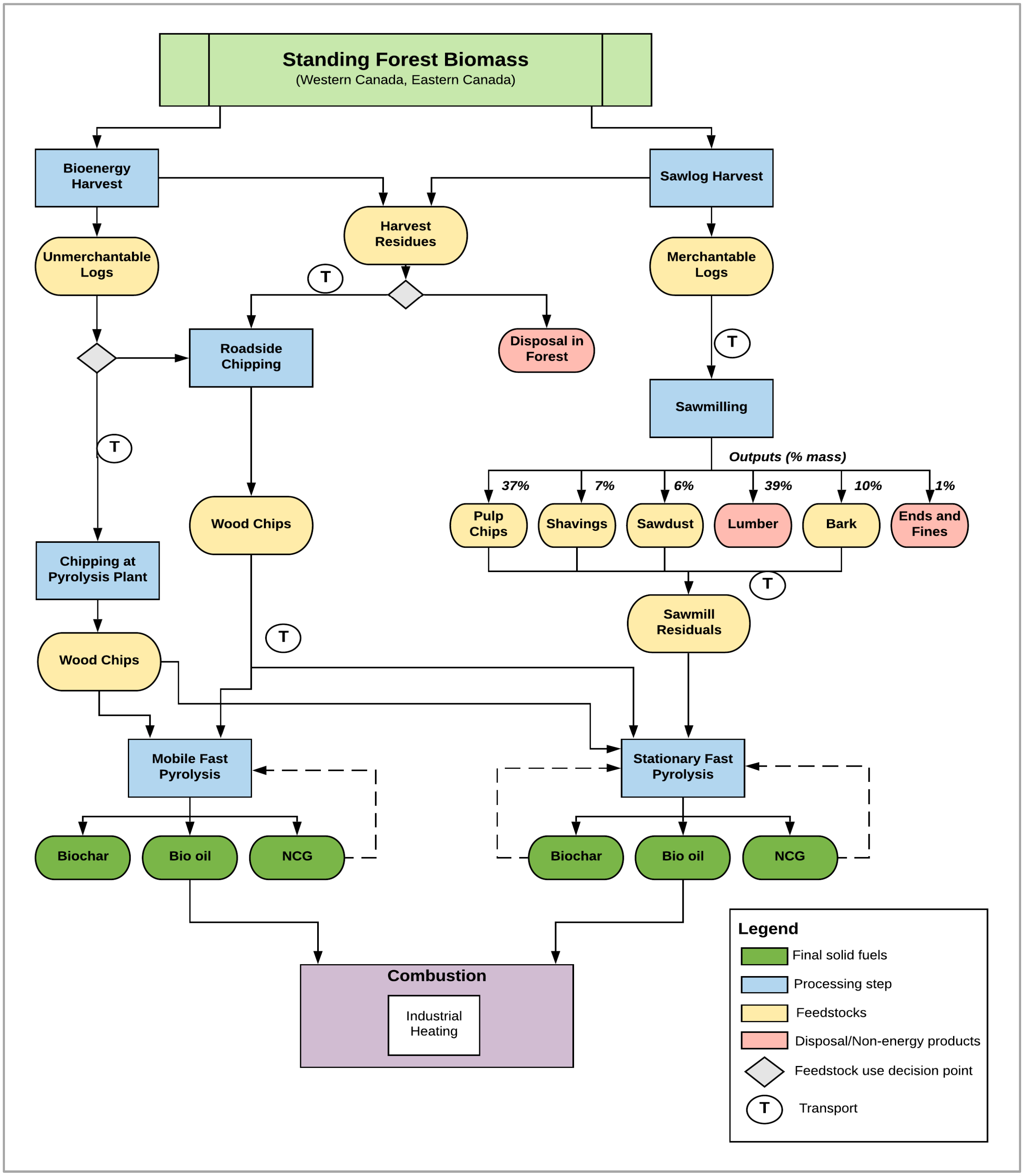

Figure 22. System boundaries and life cycle activities for bio oil production from two types of fast pyrolysis using wood biomass feedstocks, from extraction to combustion.

11.1.2 Fuel Conversion

The current potential for pyrolysis oil production in Canada is primarily centered on fast pyrolysis, and available LCI data for pyrolysis systems are generally for fast pyrolysis. In addition, fast pyrolysis systems are known to produce greater yields of bio oil than slow pyrolysis systems. During fast pyrolysis, biomass is converted at a very high heating rate

(10-1000 degrees C/s) for a very short residence time (0.5-2.0 seconds) producing volumes of bio oil in the range of 65-80% (on a dry mass basis) (Roy & Dias, 2017). Bio oil yield is highly dependent on feedstock properties and pyrolysis parameters, with wood biomass providing the highest yields. After cooling and condensing, the resulting bio oil has a heating value of about half that of conventional oil (Danish Energy Agency, 2017). The process gas produced during pyrolysis is typically used to provide drying energy for the incoming biomass. The biochar produced has a wide range of potential applications, including onsite energy use, substitution for coal or heavy fossil fuels in industrial boilers, or as a soil amendment.

The modelling of default pathways for pyrolysis oil will be based on two Canadian fast pyrolysis systems, including a mobile fast pyrolysis plant (Ayer & Dias, 2018) and a stationary fast pyrolysis plant (S&T2 Consultants Inc., 2011).

Mobile Fast Pyrolysis

To develop the basic unit process building blocks for a mobile fast pyrolysis system for converting wood biomass to bio oil, we used LCI data from a recent publication by Ayer & Dias (2018) where operating data from a demonstration-scale mobile fast pyrolysis plant was used to model the life cycle impacts of the system in a Canadian context. The fast pyrolysis plant modeled was a 50-tonne per day mobile plant that used steel-shot fluidized bed technology and a front-end feedstock drying system. Wood biomass is fed into the front-end unit where it is dried and pulverized before being fed into the pyrolysis chamber (Figure 23). On a mass basis, the mobile fast pyrolysis unit produces approximately 65% bio oil (at 17.7 MJ/kg energy content), 20% biochar (at 25.6 MJ/kg energy content), and 15% NCG (at 12.7 MJ/kg). NCG was assumed to be used for heating energy in the pyrolysis plant, while biochar was assumed to be sold to other end users.

Stationary Fast Pyrolysis

To develop the basic unit process building blocks for a stationary, commercial scale fast pyrolysis system for converting wood biomass to bio oil, we used LCI data and information from GHGenius 4.03 ((S&T)2 Consultants Inc., 2012). Ensyn provided mass balance and energy use data for their commercial scale system which produces bio oil, biochar, and NCG from wood feedstocks. It is assumed that all biochar and NCG are fully utilized by the pyrolysis system to dry incoming feedstock and therefore no additional fuel or biomass inputs are needed for drying energy. The process flow diagram for the Ensyn pyrolysis process is shown in Figure 24.

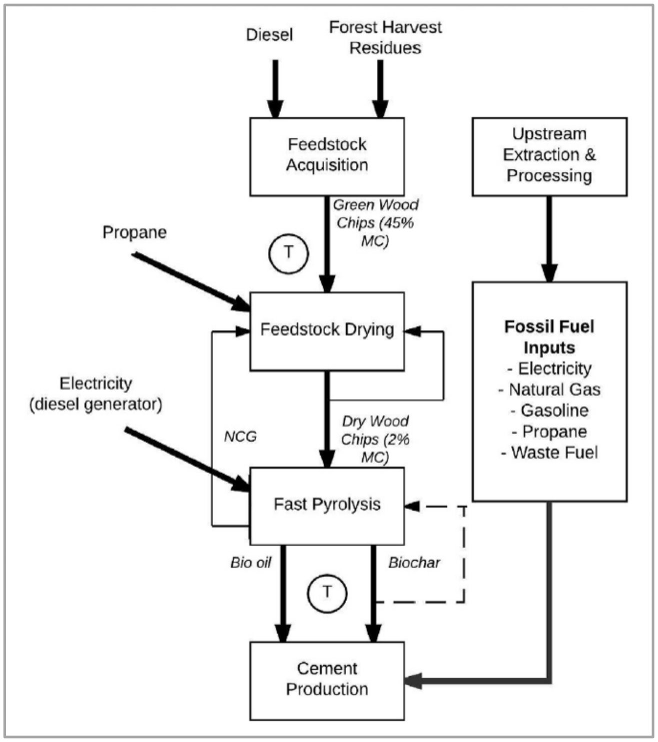

Figure 23. Overview of a mobile fast pyrolysis system using forest harvest residues to produce bio oil (Ayer & Dias, 2018).

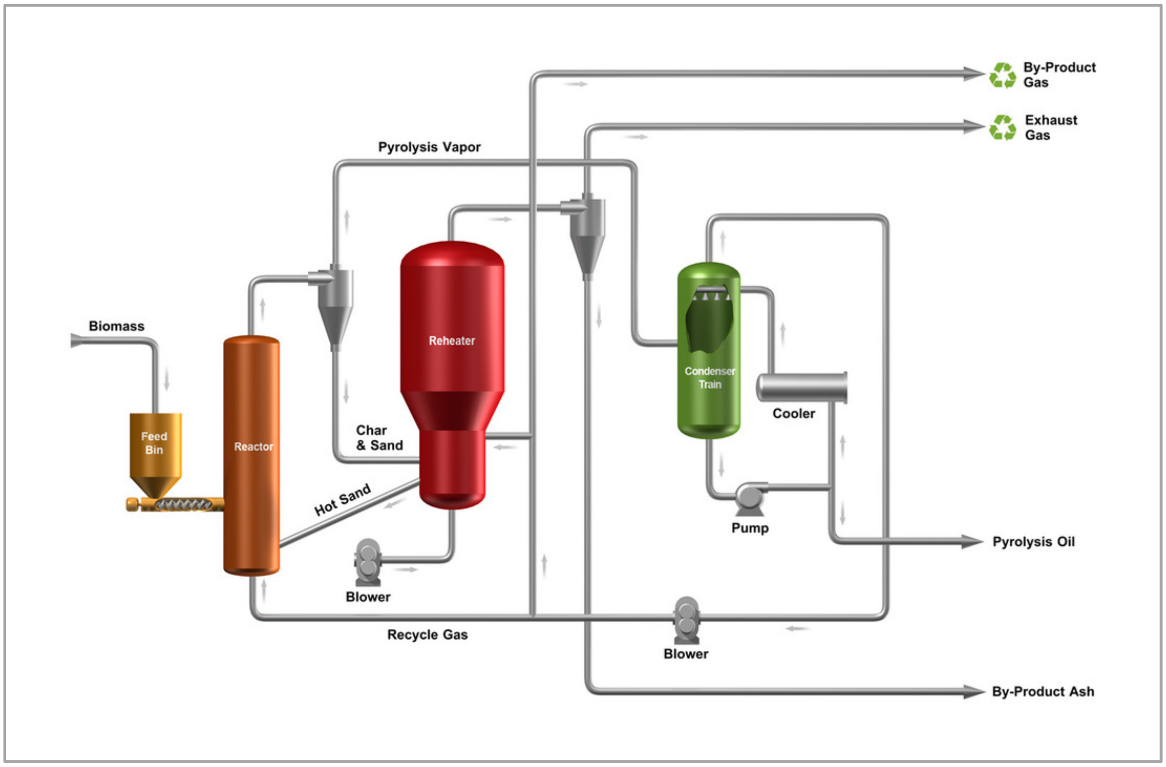

Figure 24. Process flow showing the components and steps in the Ensyn fast pyrolysis process for conversion of wood biomass to bio oil (http://www.ensyn.com/technology.html).

11.1.3 Fuel Combustion

Bio oil can be used in various energy applications, including combustion in industrial or residential boilers, cofired in power plants, blended with ethanol or diesel, or upgraded into transportation fuel (Roy & Dias, 2017). There are some challenges with each of these applications depending on the properties of the bio oil produced and the intended end use. At present, bio oil is most often considered for use in industrial furnaces and boilers due to its properties.

For the default pyrolysis oil pathways in the Fuel LCA Modelling Tool, the end use modelled for bio oil is combustion in an industrial furnace. Emissions factors for this combustion were derived from literature sources.

11.2 Life Cycle Inventory for Pyrolysis Oils

11.2.1 Feedstock Production

As shown in Figure 22, the feedstocks used in modelling bio oil production from fast pyrolysis are derived from the wood biomass feedstocks modelled for solid low carbon fuels (see Solid Wood Biomass Fuels). Transport of feedstocks to a pyrolysis plant was modeled using transport processes modeled in Milestone 2, including trucks and rail transport.

11.2.2 Fuel Conversion

Fuel conversion in mobile fast pyrolysis units was modeled using LCI data from Ayer & Dias (2018). The inputs and outputs required for feedstock drying and fast pyrolysis are shown in Table 106.

Table 106. Operating inputs and outputs for a 50 TPD mobile fast pyrolysis plant (Ayer & Dias, 2018). OD = oven dry mass; MC = moisture content.

LCI Data	Amount	Units
Feedstock Drying		
Inputs		
Green wood chips (50% MC)	3.21	kg
Propane	0.16	g
Dry wood chips (OD)	0.14	kg
Syngas (NCG)	0.23	kg
Outputs		
Dry wood chips (OD)	1.77	kg
Fast Pyrolysis		
Inputs		
Electricity (diesel generator)	0.075	kW
Dry wood chips – feedstock (OD)	1.54	kg
Dry wood chips – heating (OD)	0.09	kg
Outputs		
Bio oil (17.7 MJ)	1.0	kg
Biochar	0.31	kg
Syngas (NCG)	0.23	kg
Process Emissions		
Methane	0.0001	g

Fuel conversion of wood biomass to bio oil in a commercial scale stationary fast pyrolysis system will be modeled using LCI data from GHGenius 4.03 ((S&T)2 Consultants Inc., 2012). The operating inputs and outputs for the plant are summarized in Table 107.

Table 107. Operating inputs and outputs and process emissions for production of 1 l of bio oil from wood biomass feedstock in a commercial scale stationary fast pyrolysis system (S&T2 Consultants Inc., 2011).

LCI Data	Amount	Units
Inputs		
Dry wood	1.65	kg
Electricity	0.24	kWh
Natural gas	0.02	l
Outputs		
Bio oil (17.7 MJ/kg)	1.0	l
Process Emissions		
Methane	0.34	g/GJ of wood feedstock
Dinitrogen monoxide	1.01	g/GJ of wood feedstock

11.2.3 Fuel Combustion

Emissions factors for the combustion of pyrolysis oil derived from wood biomass for industrial heating will be obtained from Ayer & Dias (2018). These emissions factors for methane and dinitrogen monoxide were provided by Ensyn and based on testing of the bio oil produced in their commercial scale process. The emissions factor for biogenic carbon dioxide from pyrolysis oil is from an LCA study on production of bio oil using fast pyrolysis of wood biomass feedstock in the US (Steele, Puettmann, Penmetsa, & Cooper, 2012). The emissions factors are summarized in Table 108.

Table 108. Combustion emissions factors for pyrolysis oil derived from wood biomass in a fast pyrolysis process (Steele, Puettmann, Penmetsa, & Cooper, 2012) (S&T2 Consultants Inc., 2011).

Feedstock	Energy Content (HHV) (MJ/kg)	CO_2 (g/MJ)	CH_4 (g/MJ)	N_2O (g/MJ)
Pyrolysis oil (from wood)	17.5	146	0.0001	0.00005

The CO_2 emissions from combustion are considered as biogenic carbon since they are from wood biomass feedstock. As such, although these emissions will be quantified and reported separately, they will not be included in the default carbon intensity values for low carbon solid fuels.

11.3 Carbon Intensity Results for Pyrolysis Oils

CI results for pyrolysis oils are summarized in Table 109 below, including two different types of pyrolysis technologies. Results indicate that the CI for bio oil using mobile fast pyrolysis units to process chipped harvest residues and for larger-scale stationary pyrolysis of sawmill wood chips are essentially equivalent (7.9 and 7.4 g CO_2 eq. per MJ, respectively).

Table 109. Canadian average carbon intensity values for bio oil produced from mobile and stationary fast pyrolysis of wood biomass feedstocks, expressed in g CO_2 eq./MJ of fuel used in an industrial furnace.

Pyrolysis Pathway	Carbon Intensity (g CO_2 eq./MJ)
Bio oil, from mobile fast pyrolysis of harvest residues, for industrial furnace {CA}	7.9
Bio oil, from stationary fast pyrolysis of sawmill wood chips, for industrial furnace {CA}	7.4

For the mobile pyrolysis system, the primary contributors to life cycle GHG emissions are the various activities to provide wood chips for feedstock and for drying energy, including roadside chipping of harvest residues and transport of wet chips to the pyrolysis plant. For the stationary pyrolysis plant, the primary contributors to life cycle GHG emissions are the electricity use at the plant (47%) and the provision of wood chips from the sawmill (47%). Relative to the mobile pyrolysis unit, the stationary pyrolysis process is more energy intensive; however, all of the biochar produced is used onsite for drying energy which reduces the need for external inputs for drying energy such as natural gas, propane, or wood biomass. For the mobile pyrolysis system it was assumed that biochar is sold to external users; however, that system is capable of using biochar for heating, and therefore biochar could be used for drying energy in place of wood biomass, which is assumed to be the primary source in this model. This would lower the CI for mobile pyrolysis, and represents a modification that users of the Fuel LCA Modelling Tool could make depending on the set up of their system.

11.3.1 Uncertainty

Uncertainty analysis was conducted for Canadian average pyrolysis oil using Monte Carlo analysis. Results of the uncertainty analysis are shown in the violin plots in Section 12 and discussed relative to the uncertainty of other low carbon fuels in that section. Below in Table 110 the key results of the uncertainty analysis from each of the sources are summarized.

Overall the results for pyrolysis oil shows a relatively high level of uncertainty, with max values being more than or nearly double the baseline value, and min values being 50% or less of the baseline value.

Table 110. Results of uncertainty analyses for pyrolysis oils. Results based on Monte Carlo analysis of 2,000 runs with a confidence interval of 95%.

Final CI	Mean	Median	SD	Min (2.5%)	Max (97.5%)
Bio oil, mobile fast pyrolysis of harvest residues, for industrial furnace {CA}					
7.9	7.78	6.76	4.33	2.66	18.8
Bio oil, stationary fast pyrolysis of sawmill wood chips, for industrial furnace {CA}					
7.4	7.6	7.19	2.56	3.81	13.8

11.3.2 Data Gaps and Limitations for Pyrolysis Oils

Pyrolysis technologies are still an emerging part of the bioenergy sector and there is very little commercial production of pyrolysis oils for bioenergy. The data for stationary pyrolysis used in this analysis is quite dated and is not likely representative of newer operations and efficiencies. More recent primary data on pyrolysis systems for bio oil production are needed to develop more robust CI values. The results presented in this study for mobile fast pyrolysis are based on an energy allocation between bio oil, biochar, and syngas. Future users of the Fuel LCA Modelling Tool may benefit from expanding the boundary of the model to account for the use of biochar either within the pyrolysis process, or in off-site applications that could yield additional environmental benefits. Ultimately there is a wide range of pyrolysis systems being proposed, and a number of different feedstocks could potentially be used, so the system modeled in this study are very basic examples and may not be representative of the latest technology.

12.Interpretation and Conclusions

12.1 Interpretation

This study provides transparent modeling of low carbon fuels and carbon intensity values with uncertainty. It includes detailed modeling of Canadian feedstocks and conversation spanning the breadth of technology used in Canada along with many candidates for future fuels. Uncertainty has been applied at the unit process level to quantities of inputs, emissions and products as well as to the fitness for purpose of the underlying data, and at the impact level to the characterization factors.

The results presented align well with publicly available data from Canada, the US and elsewhere. The uncertainty of the results may be surprising to some readers as the variability of outputs from refineries is much higher than many studies have represented. While the study points out a number of areas where filling data gaps would reduce the uncertainty, this variability refinery to refinery is not likely to decrease over time. Uncertainty in the impact categories had minimal impact on the results.

12.1.1 Data Quality

Data quality was assessed using the pedigree matrix for uncertainty (Frischknecht, et al., 2007) on both the amount and the quality of the linked data. Data quality scores are summarized in the data sheets provided for each of the unit processes modelled.

12.1.2 Uncertainty

As indicated above, uncertainty was applied to the amounts and fitness for purpose of input and emissions data either using the variability in the process or using the pedigree matrix described in the Milestone 1 report (EarthShift Global, WSP, Introspective Systems 2019). Uncertainty was also applied to the characterization factors based on the IPCC 2013 report as shown in Appendix F of the Milestone 1 report.

In addition to the transport as discussed in Milestone 2, uncertainty in the clean fuel pathways derives from crop production, which varies greatly based on location, weather patterns in a given year and production processes, as well as from the conversion processes, many of which are still in pilot phase. This results in higher overall uncertainties in these pathways than in the more conventional pathways such as fossil fuel pathways, and to a certain extent, crop-based ethanol.

Another source of high uncertainty is in changes in soil carbon. Some studies show that practices such as no-till increase soil carbon, others indicate that it reduces the depletion of soil carbon (assumed here) and still others indicate that no-till simply moves the same amount of carbon storage from deeper regions to more shallow regions. A high range of uncertainty was applied to account for these contradictory results.

The results of the uncertainty assessment are illustrated in the violin plots below (Figure 25 and Figure 26) CIs at combustion. These include uncertainty from the inventory data alone. Each “violin” can be seen as a probability density curve which is mirror imaged. The width of the violin at a given value is proportional to the probability of that value; values in the widest portions of the violin are more probable than those in the thin tails of the distribution. There is a 90% probability the value lies within the lighter, outer envelope, while the darker core shows the 50% confidence limit.

The CIs are highly concentrated around the median CI value, as indicated by the shape of the distribution of the uncertainty in the violin plots. This indicates that the sources of uncertainty in the analysis do not cause the results to stray far from the median calculated value.

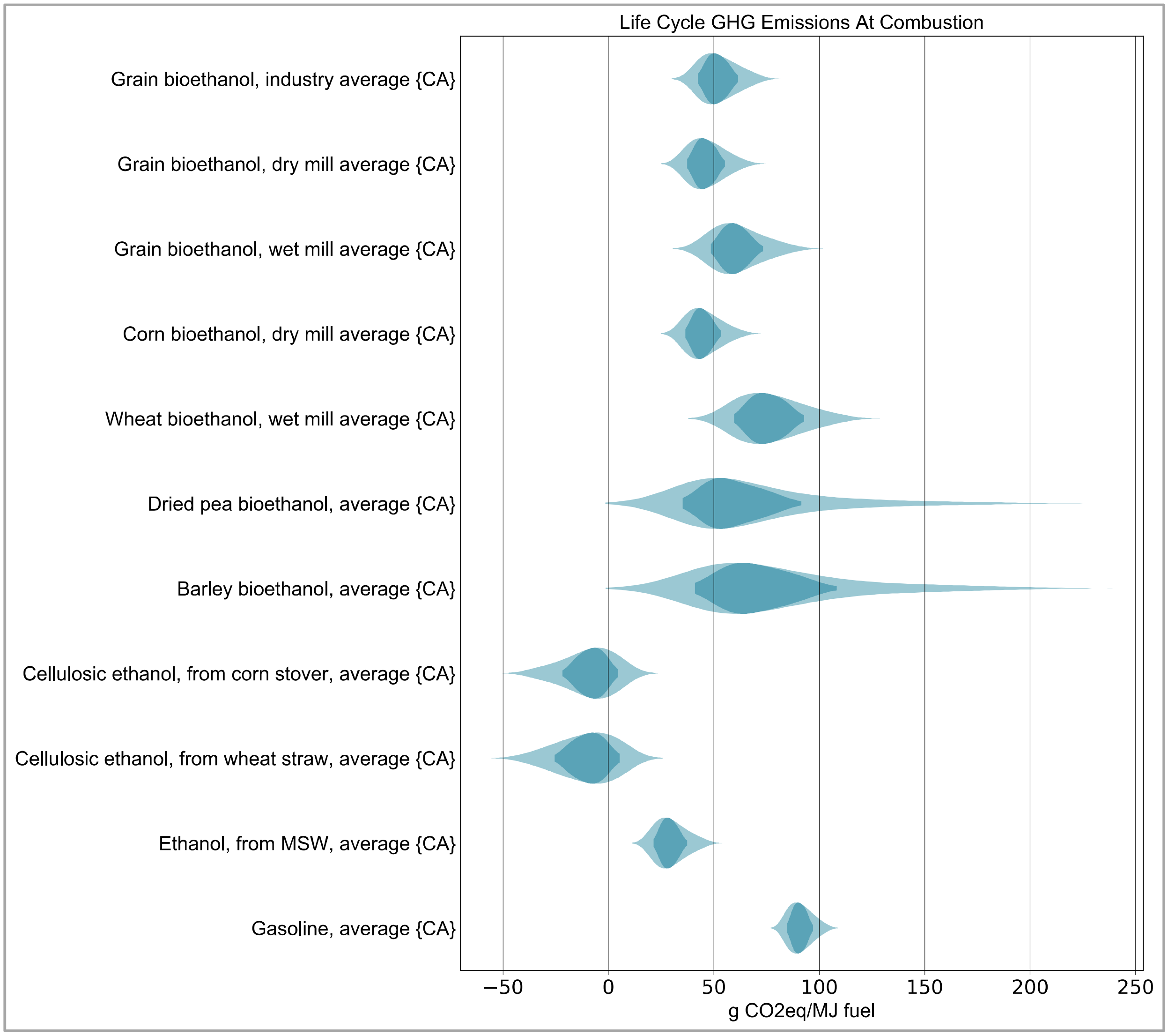

Figure 25. Uncertainty of combusted bioethanol products ("Grain" includes wheat, corn and barley unless otherwise specified), using producer reported ethanol mill facility data from CEPR reports for NRCan's ecoENERGY for Biofuels Program.

Figure 25 shows the uncertainty around the ethanol products. The top pathways are different technology and feedstock slices from industry reported data; all are less carbon intense than conventional gasoline, for which they are an analog. The most speculative processes, dried pea and pure barley bioethanols based on scaling producer-based pathways, show dramatically higher uncertainties than the other grain-based bioethanols, because the technology and agricultural CI uncertainties couple. While the electricity produced in cellulosic processes is likely to result in a credit, there is some probability there will still be an impact, and that will only increase as the rest of the grid gets cleaner.

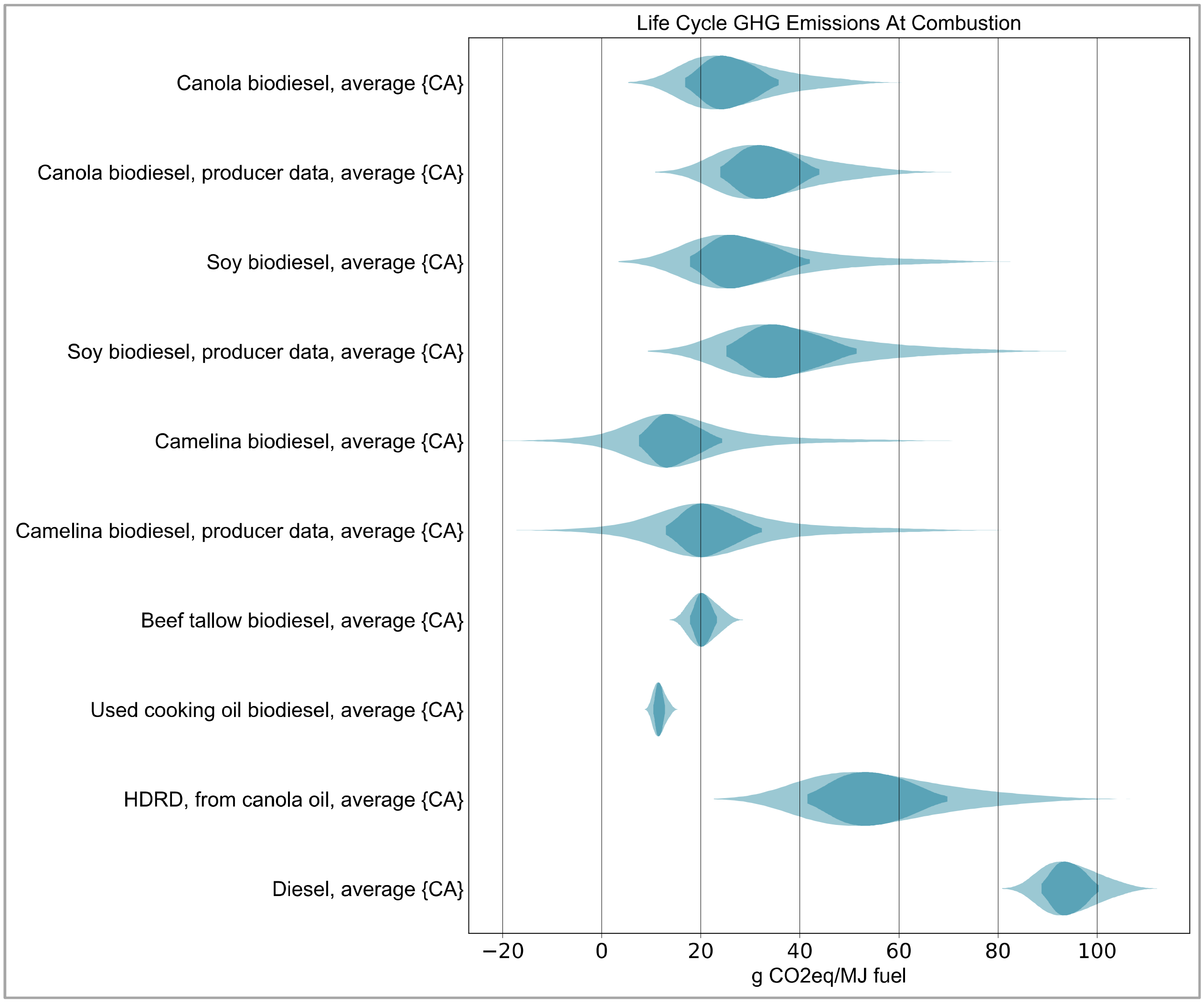

Figure 26. Uncertainty of combusted biodiesel products. 'producer data' processes represent values from CEPR reports for NRCan's ecoENERGY for Biofuels Program.

Figure 26 shows the uncertainty around the combusted CIs for biodiesels. Biodiesels from crops carry high uncertainties, again due to the feedstock uncertainties. The literature and producer-reported facility pathways are very similar because the agricultural uncertainty overwhelms uncertainties in the other life cycle stages. The impact of the large agricultural uncertainty is particularly apparent in the CI for camelina-based fuels. The wide range and negative minimum values reflect the range in soil organic carbon emissions associated with management practice change. The waste-derived biodiesels have lower uncertainty in the CI because the feedstocks carry no burden. Also, oilseeds represent a small share of current Canadian biodiesel production, so the fat-based pathways align more with facility parameters.

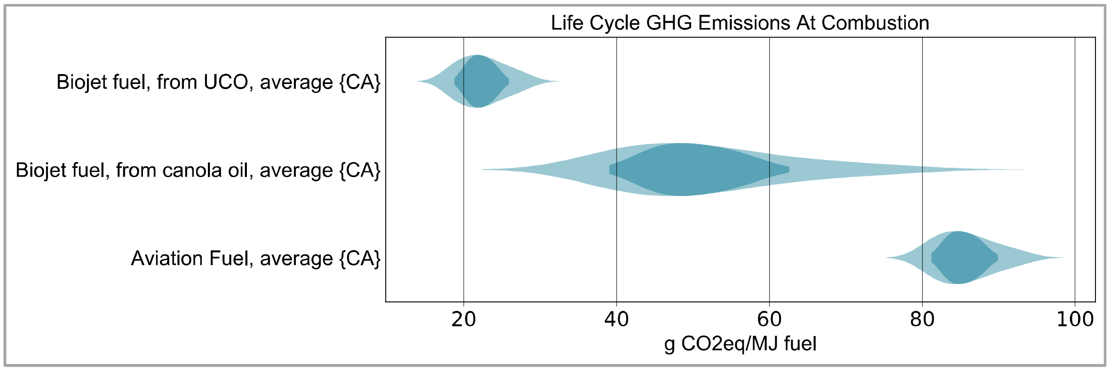

Figure 27. Uncertainty of combusted aviation products.

Figure 27 shows the uncertainty around the combusted CIs for biojet aviation fuels. Biojet fuels from crops carry far higher uncertainties, again due to the agricultural feedstock uncertainties and the more speculative nature of the HDRD pathway. Fuels from wastes have lower uncertainty in the CI because the feedstocks carry no burden.

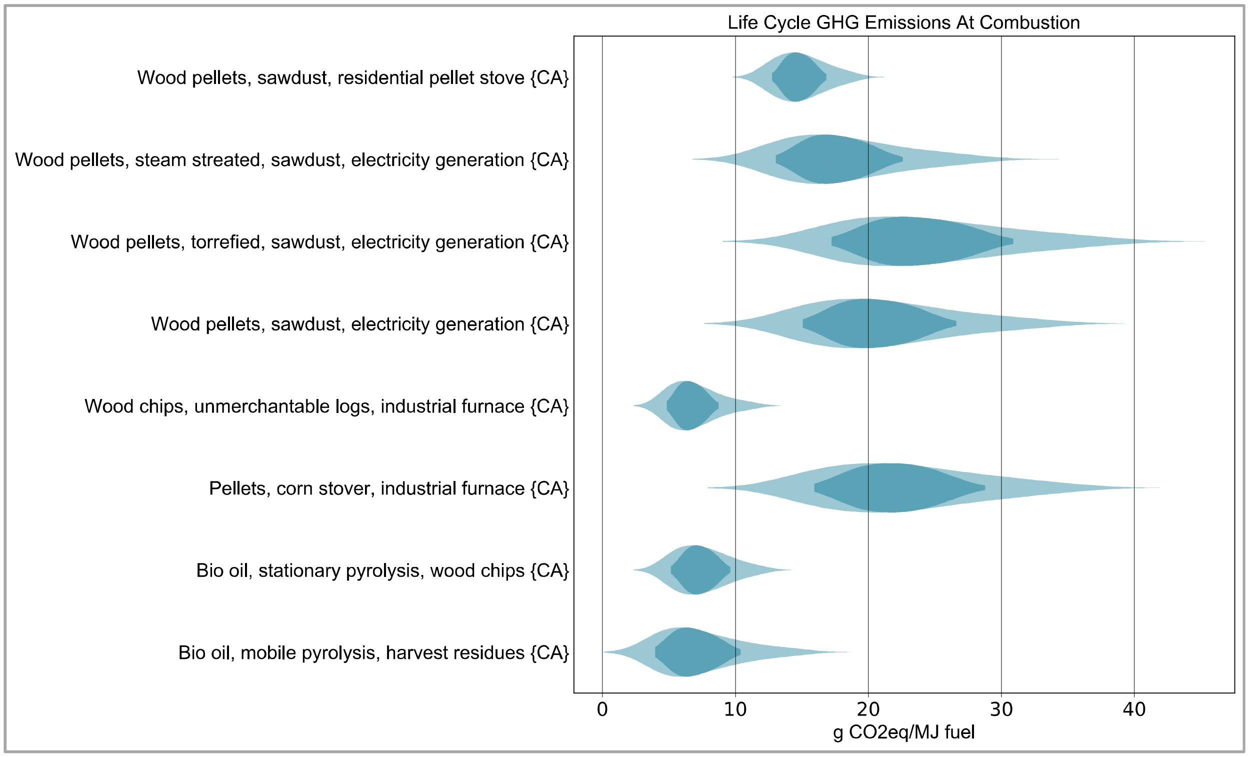

Figure 28. Uncertainties in carbon intensities from combustion of wood-derived fuels.

Wood-derived fuels have tighter distributions of the CI value as is shown in Figure 28. As no burden is assigned to the growth of the tree, there is significantly lower uncertainty in the feedstock. This is somewhat of an oversimplification, and future studies should consider work currently going on around forest carbon intensities and how they change over time.

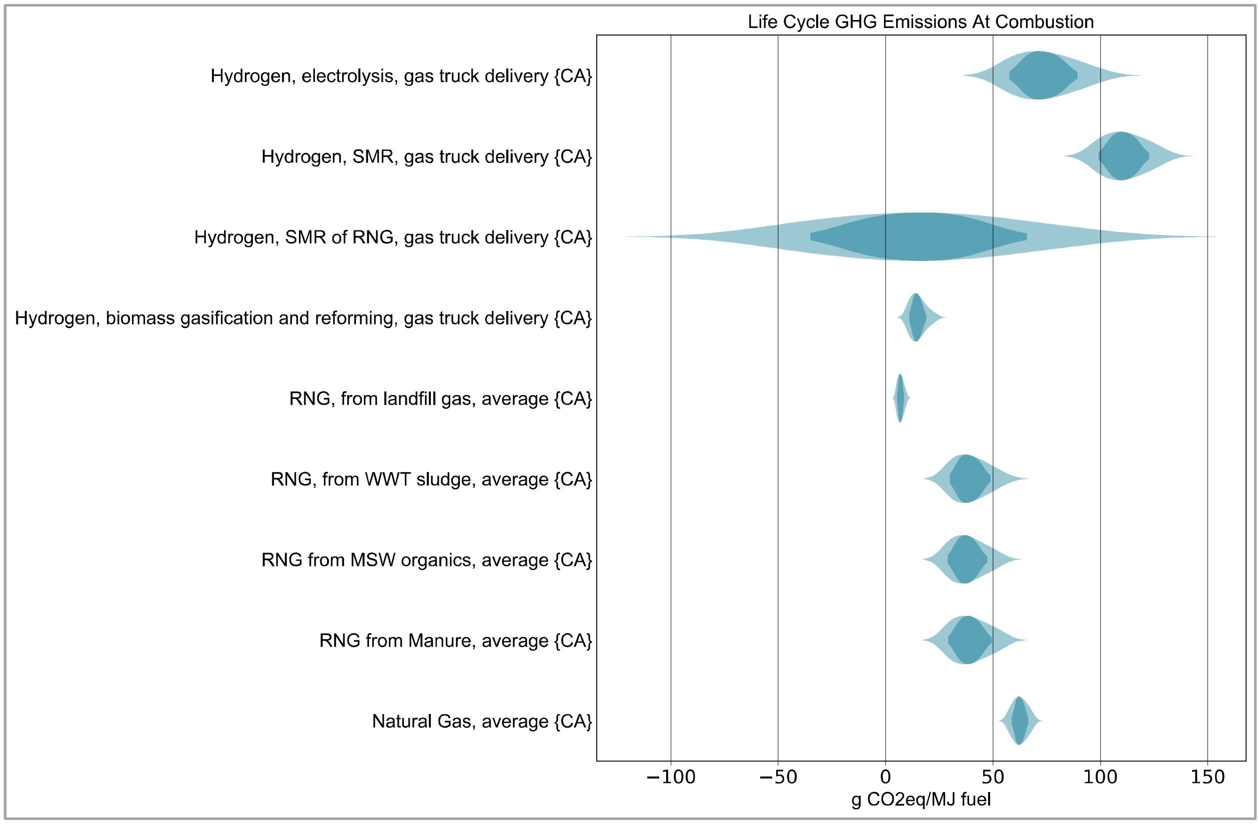

Figure 29. Uncertainty in carbon intensity of combusted hydrogen fuels.

Uncertainty in hydrogen electrolysis (Figure 29) is much higher than the other hydrogen production processes because the high variability in the electricity mix used to produce it. Standard SMR, while it has a relatively high uncertainty, is in the same range, or higher than most fossil fuels. Waste derived alternatives, such RNG and biogas, have generally both lower CIs and lower uncertainty because of lower impact in the feedstocks. Hydrogen produced via SMR of RNG shows a dramatic uncertainty range because both the SMR and RNG pathways are fairly uncertain, and when combined those uncertainties magnify.

12.2 Limitations

As with any study, there are limitations in the application of the results of this study. For this study, since only one impact category of environmental impact was considered, the interpretation of these results is limited to discussion only of GHG emissions impacts from fossil fuel production and use on the environment. Statements on the holistic impact of fossil fuels on the environment should not be made based on these results. The results also apply only to the perspective of an attributional allocation based on high heating value. Other allocations and perspectives may produce different results. Data are being gathered to allow other allocation methods to be available in the tool when is it completed.

Application of interpretation of these results should note that this study is a snapshot in time. With time, technologies, markets and supply chains will shift which will inevitably alter the carbon intensities of the considered fuel pathways. Data gaps identified throughout this study introduce some limitations in the applicability of the results and comparability with reported GHG emissions, though efforts have been made to explain and rectify discrepancies between reported and calculated emissions.

12.3 Conclusions and recommendations

12.3.1 Conclusions

The detail with which the pathways were modeled provided visibility into data gaps and where future effort should be focused. Additionally, several of the pathways identified dramatic variation year over year. Applying uncertainty to these data gaps and variability provided additional insights into how critical gathering additional data and considering a longer time period may be.

CIs external to the scope of this project play a key role in the results. In particular, there is a considerable amount of electricity which influences the final results. On the other hand, the CIs of this project could better inform the electricity CIs.

12.3.2 Recommendations

It is our recommendation that future updates to these baseline carbon intensities address known data gaps. In general, direct collection of data on inputs and outputs from facilities would improve the data quality over data collected from academic studies and public reports. Additionally, the results for both electricity and the fuels would be more robust if the electricity pathways were rolled into the tool. This would allow the electricity pathways to link to the fuels and the fuel pathways to link to the electricity, keeping both up to date. It is also recommended that future analysis include the impact of fuel production and consumption in Canada on other impact categories such as impacts to water consumption, water quality, and other emissions to air so that results can support a wholistic evaluation of environmental impacts from fossil fuels. Data gaps to be filled for each fuel and processing step are described in detail in the preceding sections.

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Appendix A: Supplemental Data and Information for Low Carbon Fuel Pathways

A1. Agrochemicals Carbon Intensity Data

The tables below expand upon the agrochemical CI data in Section 4.6 Agrochemicals upstream emissions

Table 111: Cradle-to-farm emissions for relevant agrochemical inputs included in GREET2018, in grams per kg. (ANL, 2018)

Input	CH4	N2O	CO2
Ammonia	7.55	0.05	2,382
Urea	5.48	0.04	1,048
Urea-Ammonium Nitrate Solution	11.82	5.44	3,302
Ammonium Nitrate	3.69	3.77	1,243
Ammonium Sulfate	2.04	0.01	679
Monoammonium Phosphate	2.29	0.02	960.
Diammonium Phosphate	2.84	0.02	1,113
Potash	1.01	0.01	541
Atrazine	25.07	0.26	14,703
Metolachlor	36.33	0.38	21,300
Acetochlor	36.64	0.39	21,479
Cyanazine	26.55	0.28	15,569
Insecticides	37.00	0.33	21,038

Upstream emissions from agrochemical inputs (fertilizers and pesticides) are used based on share of tracked fertilizers shipped to Canadian Agriculture, shown in Table 112.

Table 112: Canadian Fertilizer mix (Statistics Canada, 2019) and nutrient shares for each compound.

	Average Shares, 2014-2017					Nutrient Fraction, by mass			
	% total shipped	% of N	% of P	% of K	% of S	N	P	K	S
Ammonia	7%	8%				82%			
Urea	34%	40%				47%			
Urea ammonium nitrate	13%	16%				28%			
Ammonium nitrate/calcium ammonium nitrate	1%	1%				34%			
Ammonium sulphate	10%	11%			100%	28%			24%
Monoammonium phosphate	17%	20%	90%			18%	52%		
Diammonium phosphate	2%	2%	10%			18%	46%		
Potash	7%			100%				60%	
Other fertilizer products	9%								

Table 113: Nutrient and pesticide cradle-to-farm emissions based on 2014-2017 average market data (StatsCan 2019) and the GREET2018 LCI, in grams per kg.

Input	CH4	N2O	CO2
N, per kg	13.718	3.284	3602.149
P, per kg	3.054	0.027	1271.496
K, per kg	1.685	0.015	901.884
S, per kg	4.543	0.030	1511.345
Pesticide, per kg a.i.	32.316	0.329	18,817.815

A2. Grain, Seed, and Feed Compositional Factors

Table 114: Grain, Seed and Feed parameters used for crop-based biofuels.

Crops and Co-Products Factors for Crop-based Biofuels

Grain/Seed Composition Factors			Avg	SD	Min	Max	N	Source
Corn	Starch	% DM	73.4	1.6	67.5	78.8	9662	Heuzé V., Tran G., Lebas F., 2017. Maize grain. Feedipedia, a programme by INRA, CIRAD, AFZ a
	Dry Matter, % as fed	% DM	86.3	1	81.8	90.5	11	https://www.feedipedia.org/node/556
	Gross energy	MJ/kg DM	18.7	0.1	18.6	19.1	92	
	Starch relative to corn		1		1	1		
Wheat	Starch	% DM	69.1	1.9	61.8	74.9	25431	Heuzé V., Tran G., Renaudeau D., Lessire M., Lebas F., 2015. Wheat grain. Feedipedia, a progra
	Dry Matter, % as fed	% as fed	87	1.3	81.9	94.5	41570	https://www.feedipedia.org/node/223
	Gross energy	MJ/kg DM	18.2	0.2	18	18.7	328	
	Starch relative to corn		0.94141689		0.91555556	0.95050761		
Barley	Starch	% DM	59.7	2.3	52.2	66.8	9706	Heuzé V., Tran G., Nozière P., Noblet J., Renaudeau D., Lessire M., Lebas F., 2016. Barley grain.
	Dry Matter, % as fed	% as fed	87.1	1.3	82.8	91.6	17310	https://www.feedipedia.org/node/227
	Gross energy	MJ/kg DM	18.4	0.1	18.1	18.7	304	
	Crude Protein	% DM	11.8	1.1	8.5	16.1	15723	
	NDF	% DM	21.7	3.2	14.7	30	1068	
	Starch relative to corn		0.8133515		0.77333333	0.84771574		
Pea	Starch	% DM	51.3	2	43.4	57.5	9681	Heuzé V., Tran G., Giger-Reverdin S., Noblet J., Renaudeau D., Lessire M., Lebas F., 2017. Pea se
	Dry Matter, % as fed	% DM	86.5	1.2	82	90.7	22761	https://www.feedipedia.org/node/264
	Gross energy	MJ/kg DM	18.3	0.1	18.2	18.8	153	
	Crude Protein	% DM	23.9	1.4	19	28.5	14479	
	Starch relative to corn		0.69891008		0.64296296	0.72969543		
Canola	Oil content	% DM	46		40	50		Heuzé V., Tran G., Sauvant D., Lessire M., Lebas F., 2017. Rapeseeds. Feedipedia, a programme
	Ether extract (oils)	% DM	46	2.1	39.8	51	1598	https://www.feedipedia.org/node/15617
	Dry Matter, % as fed	% DM	92.3	1.1	87.3	94.9	3844	
	Gross energy	MJ/kg DM	28.8	0.7	27.7	30.6	14	
Soybean	Oil content	% DM	21		16	25		https://www.feedipedia.org/node/15617
	Ether extract (oils)	% DM	21.4	1.7	16.6	25.9	3466	Heuzé V., Tran G., Nozière P., Lessire M., Lebas F., 2017. Soybean seeds. Feedipedia, a program
	Dry Matter, % as fed	% DM	39.6	1.4	35.3	43.8	7125	https://www.feedipedia.org/node/42
	Gross energy	MJ/kg DM	23.6	0.4	22.5	24.1	51	
	(USDA shipping/storage ~13% moisture content)							
Camelina	Oil content	%	41					GREET 2018
	Oil content	%			37	47		36 and 47% oil (Przybylski, 2005) -- Heuzé V., Tran G., Lebas F., 2017. Camelina (Camelina sativ
	Gross energy	MJ/kg	34.41					GREET 2018
Meal/Cake & Feed Co-Products Factors								
Canola			Avg	SD	Min	Max	N	
Meal/Cake	Gross Energy (HHV)	MJ/kg DM	19.4	0.5	18.5	20.5	54	Heuzé V., Tran G., Sauvant D., Lessire M., Lebas F., 2018. Rapeseed meal. Feedipedia, a progra
	Dry Matter, % as fed	%	88.8	1.1	85.3	92.3	11144	https://www.feedipedia.org/node/52
Oil	Gross energy, as fed	MJ/kg DM	39.2		38.8	47.1	4	as fed (99.9% DM) INRA-CIRAD-AFZ feed tables https://feedtables.com/content/rapeseed-oil
	Gross Energy, on DM	MJ/kg	39.3		38.8	39.8	2	on DM INRA-CIRAD-AFZ feed tables https://feedtables.com/content/rapeseed-oil
Soybean			Avg	SD	Min	Max	N	
Meal	Gross Energy (HHV)	MJ/kg DM	19.7	0.2	18.8	20	63	Heuzé V., Tran G., Kaushik S., 2017. Soybean meal. Feedipedia, a programme by INRA, CIRAD,
	Dry Matter, % as fed	%	87.9	0.6	85	92.1	33523	https://www.feedipedia.org/node/674
Oil	Gross energy, as fed	MJ/kg DM	39.2		39	40.2	9	as fed (99.8% DM) INRA-CIRAD-AFZ feed tables https://feedtables.com/content/soybean-oil
	Gross Energy, on DM	MJ/kg	39.3		39.2	40.2	10	on DM INRA-CIRAD-AFZ feed tables https://feedtables.com/content/soybean-oil
Camelina		Unit	Avg	SD	Min	Max	N	
Meal	Gross Energy (HHV)	MJ/kg DM	22.1	0.9	19.6	22.1	4	Heuzé V., Tran G., Lebas F., 2017. Camelina (Camelina sativa) seeds and oil meal. Feedipedia, a
	Dry Matter, % as fed	%	90.5	2.4	86.8	93.5	9	https://www.feedipedia.org/node/4254
	Gross energy, as fed	MJ/kg DM	39.2					(GREET uses the same value for all three oils)
	Gross Energy, on DM	MJ/kg	39.3					(GREET uses the same value for all three oils)
Grain Ethanol Feed Coproducts								
Corn			Avg	SD	Min	Max	N	
DDGS	Gross Energy (HHV)	MJ/kg DM	21.4	1.2	19.9	23	32	Heuzé V., Tran G., Sauvant D., Noblet J., Renaudeau D., Bastianelli D., Lessire M., Lebas F., 201
	Dry Matter, % as fed	%	89	1.4	86.6	91.9	332	https://www.feedipedia.org/node/71
			Avg	SD	Min	Max	N	
Corn Gluten Feed	Gross Energy (HHV)	MJ/kg DM	18.8	0.3	18.3	19.5	28	Heuzé V., Tran G., Sauvant D., Renaudeau D., Lessire M., Lebas F., 2015. Corn gluten feed. Fee
	Dry Matter, % as fed	%	88.3	1.5	84.3	94.5	6415	https://www.feedipedia.org/node/714
			Avg	SD	Min	Max	N	
Corn Gluten Meal	Gross Energy (HHV)	MJ/kg DM	23.1	0.8	21.2	24.1	36	Heuzé V., Tran G., Sauvant D., Renaudeau D., Lessire M., Lebas F., 2018. Corn gluten meal. Fee
	Dry Matter, % as fed	%	90	1.7	87.3	96.2	1662	https://www.feedipedia.org/node/715
Wheat			Avg	SD	Min	Max	N	
Wheat DDGS	Gross Energy (HHV)	MJ/kg DM	20.5	0.4	20	21.5	15	Heuzé V., Tran G., Sauvant D., Noblet J., Lessire M., Lebas F., 2017. Wheat distillers grain. Feedi
	Dry Matter, % as fed	%	90.6	1.3	88.1	94.7	182	https://www.feedipedia.org/node/4265
Pea			Avg	SD	Min	Max	N	
Pea Protein Concentra	Gross Energy (HHV)	MJ/kg DM	22.8					https://feedtables.com/content/pea-protein-concentrate
	Dry Matter, % as fed	%	93					
Barley			Avg	SD	Min	Max	N	
Malt Distillers/Draff -> Brewer's Grains								
Brewer's Grains Dehy	Gross Energy (HHV)	MJ/kg DM	19.7	1.8	17.7	22.4	8	Heuzé V., Tran G., Sauvant D., Lebas F., 2017. Brewers grains. Feedipedia, a programme by INR
	Dry Matter, % as fed	%	91	2.5	84.1	95.3	53	

Dry matter	Dry matter is calculated as the difference between the total weight and the moisture content. It is usually obtained by oven
Gross energy	Gross energy (or heat of combustion) is measured as the energy released as heat when a compound undergoes complete c

A3. Cellulosic Ethanol

Corn stover components and sugar conversion to ethanol are based on NREL 2011 report (Humbird, et al., 2011). Wheat straw analysis is based on a 2010 paper published in Biotechnology for Biofuels and will follow the same conversion assumptions for sugars as in the NREL 2011 study (Erdei, et al., 2010).

Table 115: Corn stover sugar composition and yield per 1,000 kg

Component sugar	% dry weight	Fraction	Yield	Unit
glucan (cellulose)	35.05	35.05%	350.5	kg glucan
xylan	19.53	19.53%	195.3	kg xylan
lignin	15.76	15.76%	157.6	kg lignin
arabinan	2.38	2.38%	23.8	kg arabinan
galactan	1.43	1.43%	14.3	kg galactan
mannan	0.6	0.60%	6	kg mannan
sucrose	0.77	0.77%	7.7	kg sucrose

Table 116: Wheat straw composition and yield per 1,000 kg

Component sugar	% dry weight	Fraction	Yield	Unit
glucan (cellulose)	38.8	38.80%	388	kg glucan
xylan	22.2	22.20%	222	kg xylan
lignin	18.5	18.50%	185	kg lignin
arabinan	4.7	4.70%	47	kg arabinan
galactan	2.7	2.70%	27	kg galactan
mannan	1.7	1.70%	17	kg mannan
sucrose		0.00%	0	kg sucrose

Table 117: Sugar conversion reaction during pretreatment

Input number of sugars	Input sugar type	Output number of sugars	Output sugar type	% converted to product	Ratio of conversion
1	glucan	1	glucose	9.90%	0.099
1	sucrose	1	glucose	100.00%	1
1	xylan	1	xylose	90.00%	0.9
Note: Sugar oligomers are considered soluble but not fermentable therefore xylan to xylose oligomer does not yield ethanol.					

Table 118: Sugar conversion during enzymatic hydrolysis

Input number of sugars	Input sugar type	Output number of sugars	Output sugar type	% converted to product
1	glucan	1	glucose	4.00%
1	glucan	0.5	cellobiose	1.20%
1	glucan	1	glucose	90.00%
1	cellobiose	2	glucose	100.00%

Table 119: Ethanol fermentation conversion description and percentages

Conversion description	Percent
Overall cellulose to ethanol conversion	87%
Xylose to ethanol fermentation conversion	79%

Appendix B: Transmission and Distribution

B1. Overview

The production, distribution and consumption of biofuels requires a series of transportation steps. This report provides an overview of the transportation processes required to model the variety of feedstocks and biofuels applicable in Canada.

The transportation unit processes that are included in the Fuel LCA Modelling Tool are summarized in Table 120. These models were applied selectively to represent the transportation steps involved in each feedstock and biofuels pathway. The unit processes in the Fuel LCA Modelling Tool will contain model parameters (e.g. load and distance) so that they can be adapted to the specific conditions relevant for each pathway.

Table 120. Summary of transportation processes to be modelled for low carbon fuels.

Mode of Transport	Feedstock Transport	Fuel Distribution	Regional/Proximity Considerations	Modelling Considerations and Parameters
Truck	• Agricultural • Forestry	• Conventional biofuels • Biomass (raw and pellet)	• Considered for local transportation and delivery of biofuel and biomass products to end users • Local supply is a key determinant for regional variability of feedstocks • End-user proximity is a key determinate for fuel distribution	• Load (mass) • Distance • Forestry feedstocks require additional transportation steps depending on source and production pathway (e.g. transport to road-side wood chipping) • Water content of feedstocks and biomass affects vehicle efficiency
Rail	• Agricultural	• Conventional biofuels	• Considered for longer-distance transportation (anticipated to be more relevant in mature biofuels industry)	• Load (mass) • Distance • Water content of feedstocks and biomass affects vehicle efficiency
Pipeline	• Natural gas	• Hydrogen • Renewable natural gas	• Cross-provincial transportation of natural gas (as feedstock for hydrogen production) • Local distribution networks for hydrogen and renewable natural gas	• Load (volume) • Distance

Further descriptions of these processes as well as an overview of the modelling approach and a summary of the data sources that were used to develop the LCI for modelling transportation are provided in the sections below.

B2. System Boundaries and Descriptions for Transportation

The system boundaries for transportation include the transportation of feedstocks and biofuels from origin to combustion in Canada. The boundaries include transportation between the facility boundaries of the process stages included in the Fuel LCA Modelling Tool. In the case of imported fuels and feedstocks, the origin is the point of entry into Canada.

Transportation processes typically include the following stages:

- Feedstock transportation – transport of feedstock from source (forest, agriculture, waste recovery stream, etc.) to production facility (mills, distilleries, etc.); and
- Fuel distribution – transport of biofuels from production facility to distribution facilities and then to consumer

The modelling of transportation excludes the following:

- Transportation occurring outside of Canada;
- On-site transportation (within facility boundaries); and
- Transportation of all materials other than feedstocks and biofuels (i.e. transportation of consumables, wastes and co-products are excluded)

Agricultural feedstocks

Biofuels including bioethanol, biodiesel, cellulosic ethanol and some biomass can be derived from agricultural feedstocks. Transportation of these feedstocks involves truck and rail shipments to regional production facilities. The resulting fuels are then transported to end users, typically by truck. The proximity of production facilities to source feedstocks and consumer markets is the largest determinant of transportation-related GHG emissions.

Over 97% of bioethanol production in Canada is derived from corn, with the balance coming from wheat (Natural Resources Canada, 2019). Ontario generates 60% of Canada's production, derived from corn, while 18% is produced in Saskatchewan, derived from wheat and corn. The remainder comes from other provinces (Ethanol Producer Magazine, 2019).

Saskatchewan currently accounts for 54% of Canadian crop-derived biodiesel production, which is derived from canola seeds or oil. Ontario is responsible for 33% of production, derived from canola and soybean feedstocks. The balance of production occurs in Alberta and is derived from oilseeds and animal fats (Biodiesel Magazine, 2019).

Cellulosic ethanol derived from corn stover and wheat straw, while not yet produced at a commercial scale, is expected to be similar to the transportation networks of existing bioethanol production facilities. Specifically, facilities are expected to be located in close proximity to source feedstocks and serve local markets.

Solid biofuels (biomass) pellets, while typically derived from forestry or waste-related feedstocks, can also be produced from agricultural crop residues including corn stover and wheat straw. There are no commercial-scale facilities in Canada. However, it is anticipated that these facilities would need to be situated in close proximity to both the feedstock source and end-user (e.g. on-farm drying, industrial boiler, generating station, etc.) in order to be economically viable.

Forestry feedstocks

Most solid biofuels (biomass) in Canada are derived from forestry feedstocks. Wood fibre feedstocks include:

- Unmerchantable logs - wood chips produced directly from harvested forest biomass that is not suitable for timber or pulp and paper production;

- Forest harvest residues - wood chips produced from primary forest harvest residues (i.e. branches, tops, etc.);
- Sawmill residues - wood chips or other residuals from sawmilling (e.g. wood chips, bark, sawdust, shavings); and
- Construction and demolition waste - used wood obtained from construction and demolition (C&D) waste streams.

Each feedstock results in different transportation pathways:

- Forest harvest residues and unmerchantable logs are typically transported by truck to road-side chippers before being sent by truck to the point of combustion (un-processed) or biomass processing facilities (pellets)
- Sawmill residues are transported by truck from the mill to the point of combustion (un-processed) or biomass processing facilities (pellets)
- C&D waste feedstocks require the collection and transportation of clean (untreated) wood to a local production facility. It is assumed that the supply would need to be centralized, nearby a production facility and in large enough volume to be economical

British Columbia makes up 70% of Canadian wood pellet production. Other top producing provinces include Québec and New Brunswick (Bradburn, 2014). In Canada, most wood feedstocks are made into pellets and 90% of pellet production is derived from sawmill residues.

Pellet production facilities tend to be located in close proximity to the source of their feedstocks (e.g. sawmills and forests). Biomass fuels are typically sent to industrial boilers and furnaces, distributed for institutional or residential space heating, or delivered to thermal power plants. The point of combustion for biomass fuels tends to be near the production facility to reduce transportation requirements.

Renewable Natural Gas

Renewable natural gas can be produced from municipal solid waste and sludge from wastewater treatment plants. Transportation of the gas can utilize existing natural gas pipelines if the gas is pre-treated to pipeline specifications. Un-treated renewable natural gas requires other means of transportation, including by truck. As a result, the end-users of un-treated gas tend to be in close proximity to renewable natural gas facilities.

More information on the transport and distribution for the renewable natural gas pathways will be provided later in Milestone 3 after completion of the sole-source contractor work.

Hydrogen

Hydrogen feedstocks include natural gas, renewable natural gas, syngas and water. Transportation of the feedstocks to the hydrogen production facility occurs via pipeline. Once produced, transmission of hydrogen gas from the production facility can include:

- Pipeline to a local distribution centre
- Trucking from the production facility or distribution centre to the end user (e.g. dispensing station)

In each case, the transport of hydrogen requires compression, storage and dispensing facilities. Storage is assumed to be done using geologic formations that are adjacent to the production facility. A compressor is used to extract the hydrogen and reach pipeline pressure.

Truck transportation can involve a tanker truck carrying compressed, gaseous hydrogen or liquefied hydrogen in cryogenic tanks.

B3. Modelling Approach for Transportation

The modelling approach for transportation processes in Milestone 3 focuses on providing unit processes that can be adapted to model relevant processes for the range of feedstock and biofuel pathways in Canada. This will allow the teams developing biofuel pathway models, including low carbon fuel producers, to develop carbon intensities for their unique low carbon fuel pathways by applying and modifying the basic unit processes provided in this report.

The following sections provide a brief overview of the modelling approach for transportation, as well as discussion of some key methodological issues to be addressed in the modelling.

Consistency with fossil fuel transportation models in Milestone 2

The unit processes for transportation of biofuels and their feedstocks applies the same underlying assumptions and data used to model conventional fossil fuel pathways in Milestone 2. This includes the following key assumptions and data:

- Transportation involves the same equipment and conventional fossil fuels currently used in Canada (i.e. biofuels are not used as an energy source for transportation);
- The energy and carbon intensity of equipment is the same as modelled during Milestone 2, including trucks, rail and gas pipelines;
- The system boundaries are consistent with Milestone 2, including the upstream emissions associated with conventional fuels used to power mobile equipment and excluding indirect land use change and production and decommissioning of mobile equipment and transportation infrastructure.

Additional modelling required to represent biofuels pathways include:

- Additional equipment and processes, when relevant;
- Default values for transportation distances;
- Analysis of distribution pathways and methods likely to be employed to produce, process and deliver biofuels in Canada;
- Regional analysis.

Development of Unit Process Building Blocks

The overall modelling approach for Milestone 3 was to develop unit processes to serve as building blocks for current and future modelling work in the Fuel LCA Modelling Tool. Unit processes representing transportation were selected and applied in each biofuel pathway. To ensure that the unit processes can cover each pathway, the following steps were taken:

- Review interim model development for each biofuel pathway;

- Identify transportation processes needed to model each pathway;
- Assess the variation across pathways and production methods, including regional and technological factors;
- Determine the most appropriate system boundaries for each unit process, such that the unit processes can be efficiently selected and applied to each pathway;
- Identify model parameters to allow for the customization of unit processes to reflect unique or changing conditions (e.g. load and transportation distance).

Regional Variation and Proximity

Regional variations in transportation arise from the variation in source locations for biofuel feedstocks, proximity of associated production facilities and proximity of end users (i.e. point of combustion). As the pathways being modelled are largely nascent or theoretical, average transportation distances are estimated using modelling assumptions and an underlying understanding of feedstock locations and population density in Canada.

Biofuel Feedstocks

Transport of feedstocks will assume the primary mode(s) or transport and estimate the average transport distance based on feedstock locations and existing or likely locations of processing facilities. In the absence of data, the locations of new production facilities are assumed to be similar to existing facilities, based on similar economic drivers (i.e. proximity to source and end users, labour and consumables). An average distance of 100 km between feedstock source and production facility is assumed, based on the following observations:

- Existing wood pellet facilities are adjacent or near forestry harvest operations and sawmills;
- Agricultural feedstocks for bioethanol facilities are typically regional sources (e.g. wheat in Saskatchewan and corn in Ontario);
- Short-distance transport improves the economic viability of biofuels and is expected to influence commercial viability of emerging technologies that have not reached commercial scale in Canada.

Based on this distance, trucking has been selected as the default mode of transportation for agricultural and forestry feedstocks. As the biofuels industry develops, longer distance transport may become more viable. As a result, rail transport will also be modelled and available to users of the tool.

Biofuel markets (end-users)

The distance biofuels must travel to reach end-users depends on the location of production facilities, the properties and applications of the biofuel and the distribution of end-users. As the number of production facilities and technologies are expected to increase, assumptions are required to model the average default distance that biofuels travel.

The distance biofuels and hydrogen must travel to reach end users is modelled based on conventional fossil fuel refining capacity in Canada. This approach aligns with Milestone 2 and is reasonable given the similarity of fossil and low-carbon transportation fuel markets and the blending of fossil and low-carbon fuels which occurs post-refining. The following steps were taken to estimate the average distance between production facilities, distribution centres and population centres across Canada:

1. Approximate the location of biofuels production facilities based on the location of existing refinery capacity across Canada;
2. Calculate the distance between production facilities and local population centres;
3. Calculate the average distance to rural populations within the host province;
4. Calculate the population weighted average to end-user;
5. Estimate the average distance to market by calculating the production weighted average of production facilities in Canada.

While bioethanol and biodiesel production primarily serve local markets by truck, rail has been incorporated into the model to provide an option for longer distance transport to local distribution facilities. The default distance for rail was modelled based on the weighted average distance between production centres in Saskatchewan and Ontario and population centers for each province and territory. An average one-way distance of 600 km resulted from the analysis.

The average distance calculation for biomass was modelled based on existing production facilities in Canada. Unlike transportation biofuels, the market for biomass tends to be adjacent or nearby production facilities and is often associated with the forestry sector itself. In this model, the default distance to transport un-processed wood biomass and pellets is set to 100 km.

The production of renewable natural gas from municipal waste and wastewater treatment plant sludges occurs near population centres. As a result, it is assumed that the delivery of gas through existing pipeline distribution systems is local. The default distance for transporting renewable natural gas by pipeline is set to 50 km.

Transportation Pathways and Utilization

The GHG emissions intensity of transportation depends on the degree that mobile equipment is efficiently utilized. Unless noted, the following approach was used to model the utilization of equipment:

- All local deliveries by truck are assumed to be one-way deliveries with an empty return trip. In these cases, the model attributes the emissions of the return trip to the biofuel pathway (i.e. two-way trip)
- All deliveries by rail or long-distance truck are assumed to be one-way deliveries with the return trip utilized by other product systems. In these cases, the model only attributes the emissions of first trip to the biofuel pathway (i.e. one-way trip)

Product characteristics

Product characteristics for feedstocks and biofuels impact the GHG emissions resulting from transportation. Moisture content in feedstocks and biomass can vary substantially (between 5% and up to 40%), increasing the transportation load required to deliver the equivalent dry mass or energy content. The variation in the density of feedstocks (including packing factor) can also influence vehicle efficiency during transport. Vehicle capacity may be volume dependent (and not mass dependent) for lighter, high volume materials.

To account for these differences, the following approach and assumptions were made:

- Moisture content will be included as an operating parameter in truck and rail transport unit processes. The user can enter the mass of biofuel (at pre-defined product specifications) and moisture content. The GHG emissions intensity will be based on total wet mass
- The vehicle capacity is determined by the mass of the cargo and not based on volume for all biomass and biofuels (the assumption is that the density is high enough that mass is the determinant of fuel efficiency)

B4. Lifecycle Inventory for Transportation

Transport modes and GHG intensity

Transport modes used to deliver biofuels feedstocks and biofuels include trucking, rail and gas pipeline. The modelling of the GHG intensity of each transport mode was developed during Milestone 2 for conventional fossil fuels. This data has been extracted from the Milestone 2 report and presented in Table 121. These values were used in combination with the Canadian default GHG intensities of the fuel sources to arrive at a GHG intensity for transportation in units of g CO_2 eq./tkm (total load/wet mass).

Table 121. Fuel consumption intensity of transport modes for feedstocks and biofuels

Mode of Transport	Fuel Intensity Value	Fuel Source
Truck	0.0358 liters/tkm.	• Diesel
Rail	0.00456 litres/tkm	• Diesel
Pipeline	1641 btu / ton.mile	• 98% natural gas • 2% electricity

Average transportation distances

In the absence of facility-specific location data, users of the tool can use the default distances in Table 122 reflecting approximated average feedstock transportation and fuel distribution in Canada. These distances were also used in calculating the default CI values for low carbon fuels. Refer to section B3 for the model basis for selecting default distances.

Table 122. Canadian average and default transportation distances for feedstocks and biofuels.

Life Cycle Stage	Biofuel/Feedstock	Average Distance	Primary Mode	Model Basis
Feedstock Transport	Forestry feedstocks	100 km	Truck	Approximated based on proximity of forestry production facilities to source (e.g. sawmills, etc.)
Feedstock Transport	Agricultural feedstocks	100 km	Truck	Assumed based on use of local feedstocks and favourable economics of short-distance transport

Feedstock Transport	Natural gas (feedstock for hydrogen)	2560 km	Pipeline	Approximated average distance used in Milestone 2 report
Feedstock Transport	Cooking oils / yellow grease	100 km	Truck	Assumed based on proximity of biodiesel facilities to population centres in Ontario
Fuel Distribution	Hydrogen	290 km	Truck	Assumed using method used in Milestone 2 report
Fuel Distribution	Renewable natural gas	50 km	Pipeline	Assumed based on coincidence of population density and feedstocks (e.g. municipal solid waste)
Fuel Distribution	Biomass (un-processed, pellet)	100 km	Truck	Approximated based on proximity of forestry production facilities to source (e.g. sawmills, etc.)
Fuel Distribution	Biofuels (liquids)	290 km	Truck	Approximated based on distance to population centres (aligning with Milestone 2 report)
Fuel Transport to Distribution Centre (Long Distance only)	Biofuels (liquids)	600 km	Rail	Approximated based on distance to population centres (aligning with Milestone 2 report)

Appendix C. Electricity Intensities in the Clean Fuel Standard's LCA Modeling Tool

C1. Approach

The approach for determining the electricity emission intensities in the Clean Fuel Standard's LCA modelling tool consists of relying upon publicly-available data that are further augmented by ECCC to account for indirect emissions. The direct and indirect emission intensities are modelled using Environment and Climate Change Canada's *National Inventory Report (NIR) 1990-2015: Greenhouse Gas Sources and* Sinks in Canada and Environment and Climate Change Canada's internal tool respectively. Provincial and national grid emission intensities for the year of 2015 are provided as seen in Table 123.

Table 123. Provincial and national grid emission intensities included in the Clean Fuel Standard's LCA modelling tool. Values are for the year of 2015 and are expressed in tonne CO_2 e/GWh.

	Direct Impacts (NIR 2017 Annex 13 Part III)	Indirect Impacts (ECCC Internal Tool)	Indirect Impact Uncertainty Range		Total
			Min.	Max.	
AB	790.0	78.9	60.7	126.2	868.9
BC	12.9	63.4	55.1	84.9	76.3
MB	3.4	21.5	17.8	40.2	24.9
NB	280.0	60.9	53.1	90.2	340.9
NL	32.0	22.2	18.5	39.6	54.2
NS	600	114.9	97.8	172.7	714.9
ON	40	26.7	23.8	39.9	66.7
PEI	20	263.2	235.9	319.8	283.2
QC	1.2	10.3	7.6	20.4	11.5
SK	660.0	73.4	62.9	112.8	733.4
YK	41.0	Out of Scope	-	-	Out of Scope
NW	390.0	Out of Scope	-	-	Out of Scope
NU	Confidential Data	Out of Scope	-	-	Out of Scope
CA	140.0	34.1	28.2	53.9	174.1

C2. National Inventory Report 1990-2015: Greenhouse Gas Sources and Sinks in Canada Part 3

The NIR provides emission intensities related to the generation of electricity by the Public Electricity and Heat Production category (IPCC Category 1.A.1.a), on a national and provincial level. Auto-producers who either partially or wholly generate electricity for their own use and also may sell some of their electricity to the grid are excluded from the scope. The scope of electricity generation includes only main activity producers, entities whose main activity is the production of electricity. The emissions associated with the small amount of utility steam generation are therefore included within the scope of this category. Emission intensities reflect GHG emissions associated with electricity delivered by the grid. Energy losses in transmission and distribution are not considered.

GHG emissions reflect emissions from combustion-derived electricity. Emissions occurring offsite, as is the case for uranium fuel production and processing for nuclear power generation, are excluded from the scope. Additionally, nuclear, hydro, wind, solar and tidal electricity generators only emit small qAnhydrousntities of GHGs from the use of diesel generators as backup power supply.

Electricity generation intensity values were derived for each fuel type using GHG emission estimates and electricity generation data. GHG emissions are based on the total fuel consumed by the public utility sector, as provided in the RESD,1 while generation data are from CANSIM (2005– 2013) and the EPGTD publication (1990–2004). Regional emission factors are applied for coal and natural gas emissions however, for the remaining fuels, region-specific emission factors were not available and nationally reported emission factors are applied. The complete methodology used to develop the GHG emission intensities is discussed in Chapter 3 and Annex 3.1 of the *National Inventory Report 1990-2015: Greenhouse Gas Sources and Sinks in Canada* report.

Several Statistics Canada sources were used to provide electricity production and fuel consumption values. Publications include the *Report on Energy Supply and Demand in Canada* (RESD) (Statistics Canada 57-003-X), *Electric Power Generation, Transmission and Distribution* (EPGTD) (Statistics Canada 57-202-X) and CANSIM (Tables 1270006,127-0007 and 127-0008).

C3. ECCC Internal Tool

C 3.1. Scope

The tool is used to estimate the indirect segment of electricity emissions. Indirect emissions can be defined as emissions that do not stem from electricity generating processes. Examples of indirect emission sources include electricity transmission, use of sulfur hexafluoride during transmission, herbicides, wastewater, concrete, steel, infrastructure heating, lubricating oils, radioactive waste and vehicle operation.

C 3.1.1. Functional Unit

The tool is designed to evaluate potential environmental impacts of electricity generation from different sources, in Canada. In order for the tool's results to be included in the Clean Fuel Standard's LCA modelling tool, a functional unit of producing and delivering 1 MWh of electricity generated and distributed in Canada in 2017 was used. 2015 Canadian grid mixes were applied. The tool uses the 2013 global warming potentials implemented by the IPCC.

C. 3.1.2. Allocation Rules

Default allocation is made based on energy content. In the case of co-generation, the allocation factor splits emissions intensities (CHP operation, infrastructures when relevant and fuel supply too) on an energy content basis to prevent the steam emissions from being included in the electricity emissions.

C 3.1.3. System Boundaries

The tool assesses the life cycle impacts of electricity production in Canada, from resource mining and extraction, processing and electricity production steps, and subsequent grid step. The life cycle of all pathways is divided in four main life cycle steps, namely: fuel provision (when applicable), infrastructure construction, operation, and transmission/distribution.

Details on the lifecycle stages follow:

- The Fuel provision stage includes the extraction and refining of the fuel used to produce the electricity.
- The Infrastructure stage pertains to the plant and equipment construction itself.
- The Operation stage includes the production of electricity and all the services and products needed for this operation. Along with this stage, two sub-stages (emissions control system) appear for some pathways: the carbon capture system and the pollution control (NO_x and SO_2 emissions control).
- The Transmission/Distribution includes the infrastructure, equipment, products and services required to transport the electricity from the production site to the final user.
- The Supply and Waste management sub-systems respectively pertain, for each of the preceding subsystems, to all of the activities that stem from:
    - Resource procurement (water, energy, chemicals, materials), including the extraction, treatment and transformation of natural resources, and the various transports to the resource-use sites (i.e. pre-production, production, distribution, use and end-of-life management sites).
    - The transport and treatment/management of the waste generated during any of the product’s life cycle stages, taking all of the possible recovery options into account.

13.1.1 C 3.1.4. Geographical and temporal boundaries

Some processes within the system boundaries might take place anywhere or anytime, as long as they are needed to achieve the functional unit.

For example, the processes associated with the supply, and the waste management (background processes) can take place in Canada or elsewhere in the world. In addition, certain processes may generate emissions over a longer period than 2017. This applies to landfilling, which causes emissions (biogas and leachate) over a period whose length (several decades to over a century/millennium) depending on the design and operation of the burial cells and how the emissions are modeled in the environment.

13.1.2 C 3.1.5. Electricity Generation Pathways

Electricity pathways included in the tool include:

- Coal steam boilers with or without carbon capture systems (CCS) using different fuels (bituminous, sub-bituminous and lignite);
- Natural gas combined cycle or simple cycle turbines with or without CCS using conventional or unconventional (shale gas) natural gas;
- Biomass steam boiler with or without CCS and cogeneration boiler using biomass originating from forest, either standing wood or residue (pellets or wood chips burned in simple cycle or cogeneration plants);
- Hydropower from reservoir or run of river types;
- Onshore wind power.
- Natural gas converted boilers: this model covers the electricity produced from natural gas in ancient coal-powered plants.
- Combined heat and power (natural gas): the model covers electricity produced from natural gas originating from conventional and unconventional sites, specifically, shale gas. Cogeneration of electricity and heat is covered in this pathway.
- Solar thermal: This model covers electricity produced in concentrated solar thermal plants. As all the renewables, fuel provision stage is excluded for this pathway.
- Solar photovoltaic: This model covers electricity produced by photovoltaic panels. As all the renewables, fuel provision stage is excluded for this pathway. Different technologies and installed powers will be included in this pathway as their life cycle inventory differ.
- Nuclear: this model covers the CANDU technology of electricity production from nuclear fusion.
- Diesel (off-grid generation): this model covers the electricity produced from diesel in off-grid sites, mainly in the northern regions of the country.
- Utility-scale natural gas boilers: The model covers electricity produced from natural gas originating from conventional and unconventional sites using boilers.

C 3.2. Data Sources

Infrastructures and fuel supply are modeled using data from the ecoinvent 3.4 database as main basis and completed with Canadian and provincial data for the main parameters (installed power, provenance of the raw materials, location of mines, etc.) when available. The Operation stage data relies on Canadian data, namely NPRI for emissions, national and province statistics for other key parameters as efficiency, exchanges with other regions, etc. Transmission and distribution relies on ecoinvent 3.4 for infrastructure information and on Canadian and provinces statistics for the key parameters (km on line, losses during transport). Missing data are completed with literature sources and proxies.

C 3.3. Methodology

The tool provides emission intensities on a technology basis. A provincial emission intensity is determined by weighting each technology in relation to its share in the overall provincial grid mix. A national emission intensity is determined by weighting each technology in relation to its share in the national grid mix.

Appendix D. Supplemental Methods and Calculations Descriptions

D1. Handling Recycling in LCA

Introduction

Handling recycling of products in LCA is a special case of allocation. As shown in Figure 30, in recycling, a material has two or more lives. There are a number of different ways to consider how the burdens of these materials and the recycling process itself are divided. It is important to remember that there is no physical division between the two lives so there is no 'right' answer to the question. Different allocations are different ways of looking at the same system and will provide different insights. It is important, however, to be consistent within an analysis.

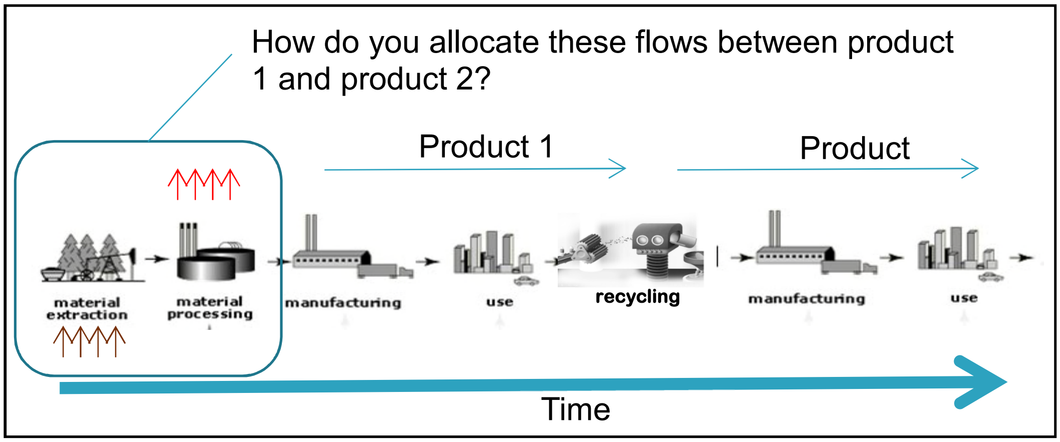

Figure 30. With recycling, two products are created at different times.

What do we need to consider?

Over the span of the two products, there are a number of activities that might be allotted to one or more of the lives, including the raw material extraction and initial processing, the collection, sorting and compost, reconditioning, packaging, transport, and what has been avoided through the reuse of the material. Different methods apportion those impacts differently to the first and second lives and may take into consideration further lives of the material. In addition to consistency between product systems, there must be consistency within a system: the same method should be used to apportion impacts at the beginning of a product life as well as at the end (e.g., incoming recycled material should be apportioned impacts through the same method as material leaving the system via the recycling bin.)

Before looking at each method in detail, it is important to start with a basic understanding of the two systems to be modeled as shown in Figure 31.

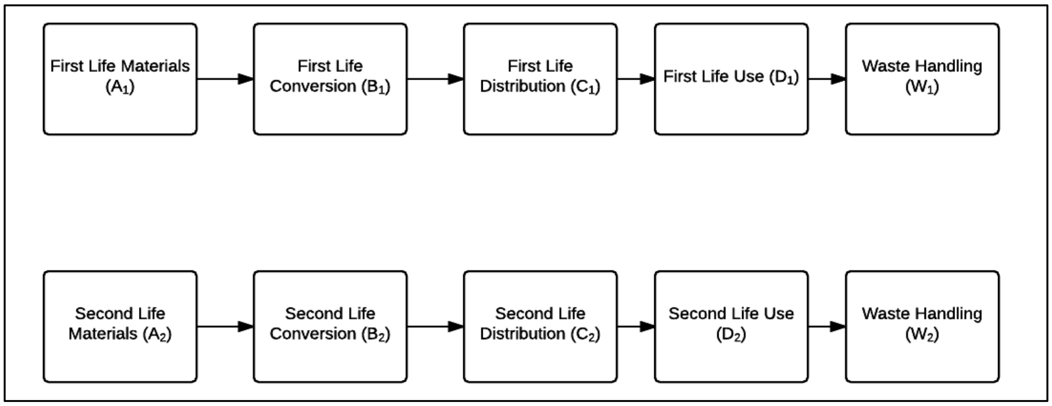

Figure 31. The processes needed to create a product which is put into the recycle bin at end of life (product 1) and the product created at time 2 (product 2) are designated by the subscript.

In both lives, there is a need for materials, conversion from materials into a product, distribution, use and then some kind of handling at end of life. These are denoted by the letters in parenthesis following the names (e.g., A_1, B_2, etc.). The subscript indicates which life the process belongs to. These indicators will be used in the equations for each LCA recycling method.

Closed Loop Allocation Procedure

ISO 14044 distinguishes two classes of recycled product: those that have the same properties as virgin material and those that have different properties (ISO 14044, 2006b). Specifically, section 4.3.4.3.3 of ISO 14044 states:

a) A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials*.
b) An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

The closed loop procedure described in a) above also goes by these other names:

1. Open-loop with closed loop procedure (ISO 14049), (ISO/TR 14049:2000(E), 2000)
2. avoided burden approach,
3. end of life approach (supported by metals industry),
4. recyclability substitution approach (ILCD Handbook) (European Commission -Joint Research Centre -Institute for Environment and Sustainability, 2010),
5. closed-loop approximation (GHG Protocol) (Bhatia, et al., 2011)
6. 0/100 approach.

The Avoided Burden or Closed Loop approach is shown in Figure 32. If the product is landfilled, it must take the burden of Waste Handling (W_1). If it is recycled, it takes the burden of the refurbishment process (I) and gets credit for the amount passed on to the second life (A_2). The second life must take the burden of the virgin material which was displaced in the first life (A_2).

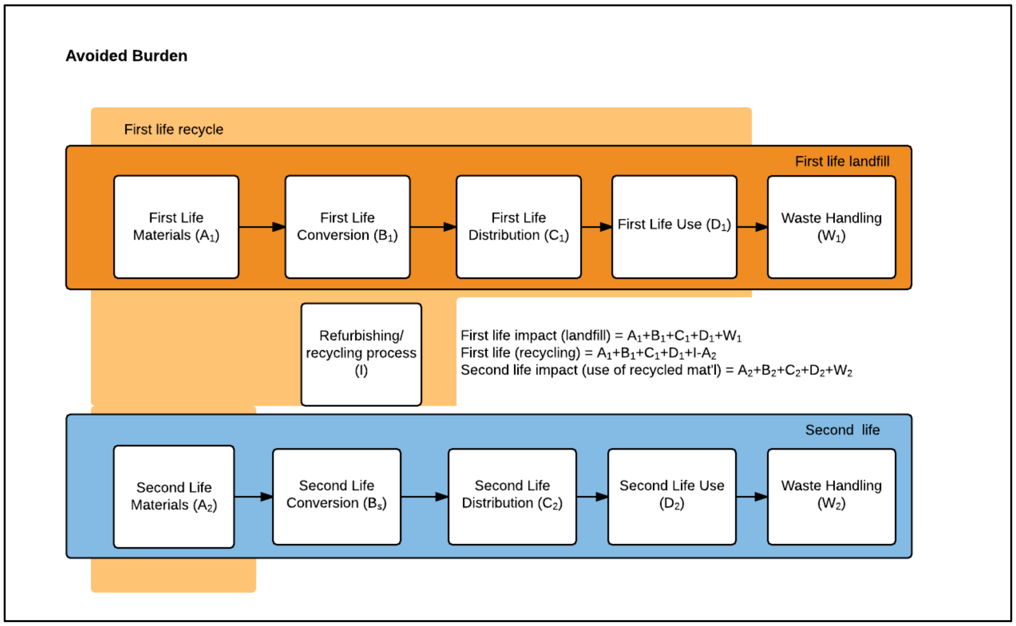

Figure 32. In the Avoided Burden or Closed Loop approach, the first life takes the burden of the recycling process but gets credit for the virgin material avoided by the second life.

The closed loop procedure encourages recycling at end of life, but does little to encourage the reuse of recycled products.

Open Loop Approaches

Economic Allocation

In economic allocation (Howard, Edwards, & Anderson, 1999), the recycled material created from the first life becomes a coproduct. The impacts of cradle to gate (A_1+B_1) are allocated between Product 1 and Product 2 based on their sale price. If the price of Product 1 is $90 and the price of product 2 is $10, The second life would take (10/(90+1)) or 10% of the burden of A_1+B_1. This method can be applied whether or not the material changes properties and is useful when the recycled product is very different from the initial product. The drawback of this method is that scrap costs can be volatile and the market in which product 1 is sold at time 1 may be very different from the market when it is recycled. Thus it is most useful for very short lived products where the economics are well understood. Economic allocation further drives market forces.

Number of uses

The number of uses approach (ISO/TR 14049:2000(E), 2000) is a method which is useful when a product degrades over consecutive life cycles and is supported by many in the paper industry (American Forest and Paper Association, 2006). Like the economic allocation method, the impacts of cradle to gate (A_1+B_1) are allocated between Product 1 and subsequent lives based on an allocation factor:

Allocation Factor for Primary product system = $(1-Z_1)+(Z_1/u)$

Allocation Factor for recycled product systems = $Z_1\ (u-1)/u$

where :

u is the number of uses (lives)

Z_1 is the percent recycled after the first use.

The drawback to the number of uses is that the modeler must know exactly how many times a product can be recycled and must know the percent being recycled at Time 2.

The number of uses method benefits both recycling at end of life and use of recycled material.

Cut off approach

One of the most used commonly used methods in LCA, the Cut Off approach (Frischknecht, LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency, 2010) draws a simple boundary between Product 1 and Product 2 at the point when the user of Product 1 puts the product in the recycle bin (Figure 33).

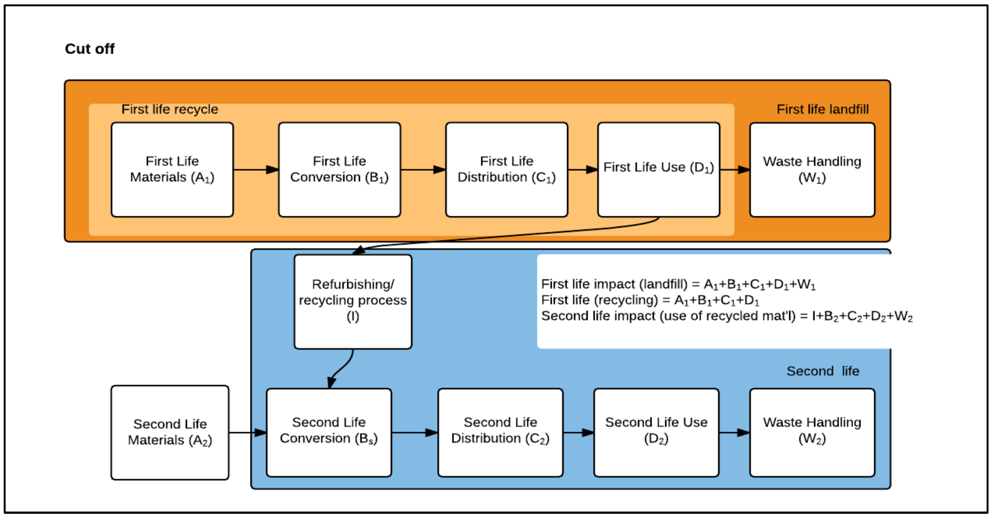

Figure 33. In the Cut-Off method, the first life takes burdens through disposal. The second life takes the material burden-free, with the exception of the refurbishing process.

This method is easier to apply than most other methods because it does not depend upon market conditions, number of uses or other data. The primary beneficiary of this approach is the user of recycled material. While the life cycle of Product 1 does not have to take the burden of landfilling or incineration, it gains no benefit from the reuse of the material.

As Frischknecht discusses in his 2010 article, the closed loop approaches are risk seeking because they borrow environmental loans from future generations. The Cut Off method, on the other hand, is risk averse: environmental burdens are strictly linked to the product that causes them, irrespective of any potential future use.

50/50 Approach

The 50/50 approach (which can also be adjusted based on how much useful material is generated from a kilogram of material at end of life) allocates 50% the burdens of (A_1+B_1) to each life (Ekvall, 2000). The equations for the impact look like this:

First life impact (landfill): $A_1 + B_1 + C_1 + D_1 + W_1$

First life (recycling): $A_1 + B_1 + C_1 + D_1 + 0.5 * I - 0.5 * (A_1 + B_1)$

Second life (use of recycled material: $0.5 * I + 0.5 * (A_1 + B_1) + B_2 + C_2 + D_2 + W_2$

In the 50/50 approach, both lives benefit from the reuse of material. If the allocation percent is 50%, it can be thought of as arbitrary, but ascertaining the exact values to use can be burdensome. This method is gaining traction with the steel industry where the amount of reused material is high and relatively well understood.

Market Model for System Expansion

The market model for system expansion or the market-based approach takes a consequential approach to end of life (Weidema, 2003). If a recycled material is fully utilized, meaning that all of the material which enters the recycling stream at end of life is reused, the consequence of using that material would be that another user would have to use virgin material. If a recycled material is underutilized, meaning that some of the material entering the recycling stream is either stockpiled, landfilled or incinerated, then the use of that material avoids the end of life impacts. The diagram for the market-based approach is a bit different from that for the other methods and is shown in Figure 34.

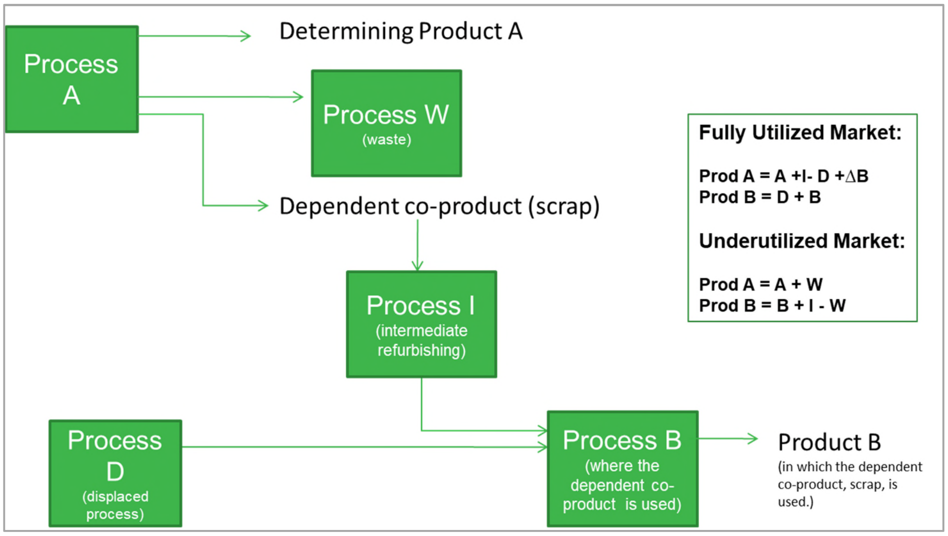

Figure 34. In the market-based approach, the burdens are allocated differently depending upon the market for recycled product.

This method is similar to the closed loop approach when recycled material is in demand. When there is little demand it is similar to Cut Off with the addition of burden for landfill or incineration for Product 1 and credit for that same end of life for Product 2.

The market-based approach requires a good understanding of market dynamics and the results will change as the market changes. *It is the only method for which different* *materials can be treated differently. It is also the only method which gives a credit for avoided landfill or incineration to the second life.* It is the method most often used in consequential studies.

Summary and Recommendations

When modeling either recycling at the end of life of a product or the reuse of a material, the choice of method will change the impacts of the product dramatically. It is important to keep a consistent perspective or burdens (and benefits) will be double counted: One cannot take a credit for something at end of life and at the same time avoid the burden of it at beginning of life.

When performing a comparative assertion, the use of the Market-Based approach under both conditions offers a comprehensive assessment of the differences between systems. Assuming a fully utilized market has the lowest impact for the first life and the highest impact for the second life. Assuming an underutilized market has the highest impact for the first life and lowest impact for the second life of any of the methods proposed to date. Thus, assessing scenarios under both conditions provides the full scope of impact.

The Market-Based approach also makes sense as a method for assessing a recycling process where the recycler has responsibility for collecting the waste material and redistributing useable product. Through its efforts, the recycler is reducing the amount of material going to landfill or incineration while reducing demands on virgin production.

Both the Market-Based approach and the Closed Loop approach seem to apply to fully utilized markets, such as aluminum and steel. Because these materials are often compared with products in underutilized markets, the Market-Based approach offers a more consistent way of modeling.

In most other cases, the Cut Off method is the preferred method for several reasons: results don’t change with changes in market conditions; it is straightforward to apply; it does not result in “credits” which are difficult to explain and justify; and it encourages the reuse of material while not discouraging recycling at end of life.

As repeated in this document, it is important that the method used is consistent:

1. At both beginning and end of life
2. For all product systems being compared

When methods are applied inconsistently, burdens may be double counted or applied inconsistently, resulting in unjustifiable conclusions.

D2. Supporting Data for Cut-Off Decisions

The following results were generated using to guide decisions around exclusion of processes from the fossil fuel and low carbon fuel life cycles. All data come from the CEDA 4 US Environmental Input/Output database. Reference can be found here: https://pubs.acs.org/doi/abs/10.1021/acs.est.9b00084

Table 124. All other petroleum and coal products manufacturing, contribution to total impact of the sector

	kg CO2 eq	Percent of total contribution
All other petroleum and coal products manufacturing	0.57564	41.2%
Petroleum refineries	0.401054	28.7%
Oil and gas extraction	0.101845	7.3%
Electric power generation, transmission, and distribution	0.08077	5.8%
Other basic organic chemical manufacturing	0.044006	3.1%
Petrochemical manufacturing	0.042443	3.0%
Natural gas distribution	0.03736	2.7%
Pipeline transportation	0.020912	1.5%
All other basic inorganic chemical manufacturing	0.008358	0.6%
Management of companies and enterprises	0.006924	0.5%
Wholesale trade	0.004722	0.3%
Truck transportation	0.004091	0.3%
Plastics material and resin manufacturing	0.003903	0.3%
Paperboard container manufacturing	0.003818	0.3%
Coating, engraving, heat treating and allied activities	0.003636	0.3%
Nonresidential maintenance and repair	0.003146	0.2%
Coal mining	0.003025	0.2%
Scientific research and development services	0.002528	0.2%
All other	0.049563	3.5%

Table 125: Natural gas distribution, contribution to total impact

	kg CO2 eq	Percent of total contribution
Natural gas distribution	2.149767	82.2%
Pipeline transportation	0.209622	8.0%
Oil and gas extraction	0.148947	5.7%
Coal mining	0.031959	1.2%
Petroleum refineries	0.005411	0.2%
Natural gas distribution	0.0052	0.2%
Electric power generation, transmission, and distribution	0.004379	0.2%
Rail transportation	0.004137	0.2%
Ornamental and architectural metal products manufacturing	0.002962	0.1%
All other	0.052045	2.0%

Table 126: Petroleum refineries, contribution to total impact

	kg CO_2 eq	Percent of total contribution
Petroleum refineries	1.244085	67.0%
Oil and gas extraction	0.258896	13.9%
Petroleum refineries	0.131072	7.1%
Electric power generation, transmission, and distribution	0.052593	2.8%
Natural gas distribution	0.045334	2.4%
Pipeline transportation	0.040938	2.2%
Other basic organic chemical manufacturing	0.013204	0.7%
Petrochemical manufacturing	0.010709	0.6%
All other basic inorganic chemical manufacturing	0.010267	0.6%
Wholesale trade	0.004479	0.2%
Nonresidential maintenance and repair	0.003809	0.2%
Management of companies and enterprises	0.003349	0.2%
All other	0.035556	1.9%

Table 127: Other basic organic chemical manufacturing (includes ethanol production), contribution to total impact

	kg CO_2 eq	Percent of total contribution
Other basic organic chemical manufacturing	1.762082	64.9%
Petrochemical manufacturing	0.268631	9.9%
Electric power generation, transmission, and distribution	0.134061	4.9%
Petroleum refineries	0.102316	3.8%
Natural gas distribution	0.081962	3.0%
Grain farming	0.059237	2.2%
All other basic inorganic chemical manufacturing	0.034874	1.3%
Alkalies and chlorine manufacturing	0.023938	0.9%
Plastics material and resin manufacturing	0.02192	0.8%
Fertilizer manufacturing	0.018851	0.7%
All other crop farming	0.0166	0.6%
Industrial gas manufacturing	0.009872	0.4%
Rail transportation	0.009333	0.3%
Wholesale trade	0.009172	0.3%
All other chemical product and preparation manufacturing	0.008582	0.3%
Fats and oils refining and blending	0.008433	0.3%
Management of companies and enterprises	0.008333	0.3%
All other	0.13049	4.8%

Table 128: Fats and oils refining and blending, contribution to total impact

	kg CO_2 eq	Percent of total contribution
Soybean and other oilseed processing	0.340427	21.8%
Oilseed farming	0.312675	20.0%
Fats and oils refining and blending	0.227836	14.6%
Grain farming	0.076857	4.9%
Wet corn milling	0.066555	4.3%
Electric power generation, transmission, and distribution	0.066358	4.3%
Animal (except poultry) slaughtering, rendering, and processing	0.035988	2.3%
Natural gas distribution	0.034197	2.2%
Rail transportation	0.019283	1.2%
Cattle ranching and farming	0.018284	1.2%
Cotton farming	0.011743	0.8%
Truck transportation	0.010568	0.7%
Paperboard container manufacturing	0.010233	0.7%
Other plastics product manufacturing	0.010149	0.7%
Dairy cattle and milk production	0.009387	0.6%
Wholesale trade	0.008834	0.6%
All other crop farming	0.008725	0.6%
Plastics bottle manufacturing	0.008538	0.5%
All other paper bag and coated and treated paper manufacturing	0.005617	0.4%
Coal mining	0.005051	0.3%
All other	0.267901	17.2%