Fuel Life Cycle Assessment Model Methodology

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Preface

The Government of Canada's *Fuel Life Cycle Assessment (LCA) Model* is a tool that allow users to calculate the life cycle carbon intensity (CI) of fuels and energy sources produced and used in Canada. The *Fuel LCA Model* uses a life cycle approach, which considers the greenhouse gas (GHG) emissions involved in multiple stages of the fuel's production process, from feedstock production to fuel combustion.

The objective of the following document entitled *Fuel LCA Model Methodology* is to explain the methodology used in the development of the *Fuel LCA Model*. The document describes the general assumptions, data sources, and calculation procedures associated with the development of the *Fuel LCA Model*.

Throughout the development of the Fuel LCA Model, Environment and Climate Change Canada (ECCC) carried out extensive quality assurance and quality control (QA/QC). The QA/QC included a review of the methodologies, calculation procedures, included data, and literature sources used to generate a CI for various fossil and low carbon-intensity fuels (LCIF).

In 2020, a draft version of the *Fuel LCA Model Methodology* report and the *Fuel LCA Model Database* were subject to a critical review performed by a panel of independent experts in the field of LCA.

A draft version of the *Fuel LCA Model Methodology* was released in December 2020 for a 75-day consultation period. Furthermore, ECCC performed beta testing of the Model Database with external stakeholders to test user functionality and garner feedback.

Results of the critical review, QA/QC and comments from stakeholders were considered for the development of the *Fuel LCA Model.*

Since the release of the January 2023 version of the Fuel LCA Model, proposed updates to the Model have been pre-published to increase transparency and to allow stakeholder to submit comments. The comments submitted have been considered during the development of the June 2024 *Fuel LCA Model.*

Ongoing development and maintenance activities are prioritized based on engagement with the Stakeholder Technical Advisory Committee (STAC), comments received from stakeholders and other governmental departments, as well as issues identified by ECCC.

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Definitions

Allocation: partition of input or output flows of a process between the product system under study and one or more other product systems (ISO 14040).

Biofuel: any liquid, gaseous or solid fuel produced from biomass.

Biogas: gaseous mixture that is recovered from the anaerobic decomposition of biomass, consists primarily of methane and carbon dioxide and contains other constituents that prevent it from meeting the standard for injection into the closest natural gas pipeline.

Biomass: comprises the biodegradable portion of products from agriculture, forestry, animal, waste and related industries. Examples include residues and waste from trees, plants and crops, food by-products, and the biodegradable portions of municipal waste.

Carbon dioxide equivalent (CO_2e): quantity of carbon dioxide that would be required to produce an equivalent warming effect over a given time period.

Carbon Intensity: in relation to a pool of a given type of fuel, this means the quantity of CO_2e in grams that is released during the activities conducted over the fuel's life cycle — including all emissions associated with the extraction or the cultivation of feedstock used to produce the fuel, with the processing, refining or upgrading of that feedstock to produce the fuel, with the transportation or distribution of that feedstock, of intermediary products or of the fuel and with the combustion of the fuel — per megajoule of energy produced during that combustion.

Characterization factor: factor derived from a characterization model which is applied to convert assigned life cycle inventory analysis result to the common unit of the category indicator (ISO 14040). Also called impact factor.

Ecosphere: consists of the entire natural environment. Examples include air, water, and natural resources.

Elementary flow: flow that is exchanged with the environment, e.g. greenhouse gas.

Feedstock: Resource that is extracted, cultivated, collected, harvested, and/or processed and delivered at the gate of the conversion plant from which fuel is produced.

Flow: Material or energy that enters or leaves a process.

Fuel pathway: a collection of unit processes, modelling parameters, and background data in the *Fuel LCA Model* that allows the determination of the carbon intensity of a fuel from a particular feedstock type.

Functional unit: quantified performance of a product system for use as a reference unit (ISO 14040).

Intermediate flow: flow that is exchanged within the technosphere i.e. human control. In the context of the *Fuel LCA Model*, any flow that is not an elementary flow.

Life cycle assessment (LCA): Compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle (ISO 14040).

Life cycle impact assessment (LCIA): Phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. (ISO 14040).

Life cycle inventory (LCI): Phase of LCA involving the compilation and quantification of inputs and outputs for a product through its life cycle (ISO 14040).

Life cycle: Consecutive and interlinked stages of a product system, for example from feedstock acquisition to combustion of the produced low carbon-intensity fuel.

Life cycle stage: collection of unit processes connected by a network of flows that models a main stage of the life cycle of a fuel. In the *Fuel LCA Model*, there are five life cycle stages: feedstock production, feedstock transportation, fuel production, fuel distribution, and fuel combustion.

Low-carbon-intensity fuel (LCIF): fuels, other than the fossil fuels, with a lower carbon intensity than fossil fuels. This definition includes hydrogen.

Monte Carlo analysis: A technique used in computer simulation that serves to generate probabilistic outcomes of a model repeatedly and that, for all the simulations, provides a randomly chosen value for each variable on the basis of each distribution of the input parameters.

System process: process that contains the LCI of a group of unit processes.

Technosphere: consists of all anthropogenic developments. Once materials from the ecosphere are extracted and in human-control, they are part of the technosphere.

Unit process: smallest element for which input and output data are quantified (ISO 14040).

Acronyms

AR5	IPCC’s Fifth Assessment Report
AR6	IPCC’s Sixth Assessment Report
CAFE3	*Canadian Analytical Framework for the Environmental Evaluation of Electricity*
CCS	Carbon capture and storage
CI	Carbon intensity
CIRAIG	International Reference Centre for the Life Cycle of Products, Processes and Services
CNG	Compressed natural gas
CRSC	Canadian Roundtable for Sustainable Crops
DDG	Distiller’s dried grains
DDGS	DDG with solubles
DQI	Data quality indicators
ECCC	Environment and Climate Change Canada
GWP	Global warming potential
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
HHV	Higher Heating Value
IEAGHG	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
LCIF	Low carbon-intensity fuel
LNG	Liquefied natural gas
NEB	National Energy Board
NETL	National Energy Technology Laboratory
NIR	National Inventory Report
MEIT	National Marine Emissions Inventory Tool
NGL	Natural gas liquids
OPGEE	Oil Production Greenhouse Gas Emissions Estimator
PRELIM	Petroleum Refinery Life-Cycle Inventory Model
RNG	Renewable natural gas
RU	Reconciliation unit
SMR	Steam methane reforming
SOC	Soil organic carbon
UNEP	United Nations Environment Programme
UCO	Used cooking oil
WDG	Wet distiller’s grain

WDGS	WDG with solubles

Chapter 1: Introduction and general principles

1.1 Presentation of the *Fuel LCA Model*

The Government of Canada has developed a *Fuel Life Cycle Assessment (LCA) Model* (the Model) to calculate the carbon intensity (CI) of fuels produced and used in Canada. The Model helps to support the delivery of regulations and programs as part of Canada's actions on climate change. The Model is robust, transparent, bilingual, and based on the Canadian context. Users of the Model could include industry, academia, LCA practitioners, governmental organizations, non-governmental organizations, and other organisations with interest in the energy sector.

The Model consists of the following three components:

1) **the Fuel LCA Model Database**: Contains a library of CI datasets and fuel pathways developed to model a CI specific to a fuel or an energy source.
2) **the Fuel LCA Model Methodology** (this document): Describes the methodology, data sources and assumptions that were used in the development of the Model. The document provides the rationale supporting the methodological approach.

the Fuel LCA Model User Manual: Provides information on general definitions and concepts related to LCA as it relates to the Model. Also provides technical guidance on how to perform basic operations in the openLCA software that are required for CI calculations.

1.2 Purpose of the *Fuel LCA Model* Methodology

The purpose of this document is to explain the methodology used in the development of the Model. It describes the general assumptions, data sources and calculation procedures used in the development of the Model. It also describes some general LCA concepts used in developing the database.

The document is divided into the following chapters:

- **Chapter 1: Introduction and general principles**: Presents the Model and provides some general concepts used in the rest of the document.
- **Chapter 2: Goal and scope of the Fuel LCA Model**: Provides the goal and scope of the Model, as well as assumptions and modelling choices used for the development of the Model Database.
- **Chapter 3: Fuel LCA Model Data Library**: Describes the modelling approach, modelling assumptions, and data sources for each category of system processes in the Model Data Library.
- **Chapter 4: Fuel Pathways**: Describes the structure of the fuel pathways and the modelling approach of configurable processes included in the Model Database.

This document is updated with each formal publication of the Model.

For instructions about how to set up and use the Model Database, please refer to the *Fuel LCA Model User Manual*.

1.3 Related standards

The Model is designed in conformity with *ISO 14040: Environmental management – Life cycle assessment – Principles and Framework* and *ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines*.

ISO 14040 provides terminology related to LCA and the structure to follow when performing an LCA. ISO 14044 provides requirements and guidelines when conducting an LCA and is used in parallel with ISO 14040.

ISO 14040: Environmental management – Lifecycle assessment – Principles and Framework

ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines

1.4 General principles and fundamentals of greenhouse gas assessments for LCIF pathways

1.4.1 Description of the general LCA concept

LCA studies are performed in a structured manner, with certain principles guiding their development. As described in ISO 14040, LCA studies consist of four phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase, which are described below.

- **Goal and scope definition**: defines the depth and breadth of the LCA study depending on the goal of the particular LCA.
- **Inventory analysis**: Lists and quantifies all emissions and extractions to and from the environment involved in the life cycle of the system being studied (e.g., the total mass of methane emitted during the life cycle, expressed in kilograms of methane).
- **Impact assessment**: Converts the inventory into indicator results (e.g., the carbon footprint in kilograms of CO_2 equivalent).
- **Interpretation**: Summarizes and discusses results to draw conclusions, make recommendations, and for decision-making, in accordance with the goal and scope definition.

Figure 1 describes the relationships between the four phases of an LCA study. LCA is an iterative process where the results of one phase can affect the outcome of both preceding and subsequent phases. The combination of the four phases of the LCA process results in a more complete picture when assessing the environmental impacts of a given process.

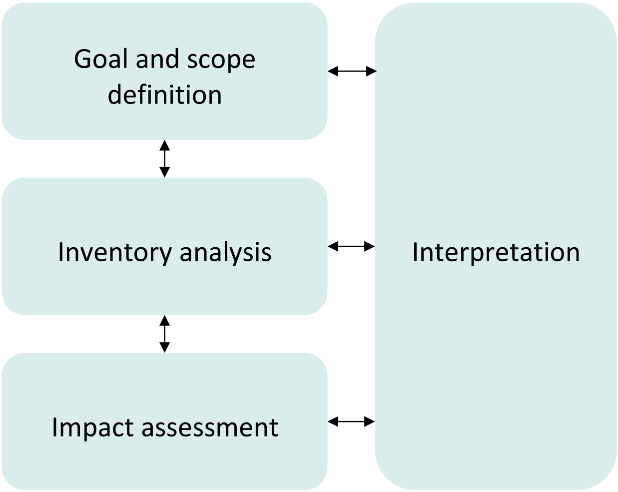

Figure 1: The four phases of an LCA study adapted from ISO 14040

1.4.2 Principles and appropriateness

Since the Model is designed in conformity with ISO 14040, it is based on many of the same principles. Some of the principles relevant to the Model are described below.

Life cycle perspective

The Model and the calculation of low carbon intensity fuel (LCIF) CIs are based on a life cycle approach. This approach, which accounts for activities from raw material extraction/acquisition to end use/combustion, allows for consideration of the environmental impacts of a full product system as well as identification of where environmental burdens exist and can be addressed or avoided.

Greenhouse gas focus

The Model only considers greenhouse gases (GHGs). In addition, as in ISO 14040, LCA's design assesses only the environmental impacts of a process. The Model does not consider economic and social factors when determining LCIF CIs.

Transparency

Transparency is an important requirement of LCA due to its complex nature. To ensure transparency, the Model includes a description of the methodology, a list of the documentation used, and calculation procedures at the unit process level (see **Chapter 0** for the definition of a unit process). Dataset (collections of data) documentation is in line with the *Global Guidance Principles for Life Cycle Assessment Databases* (UNEP, 2011).[1]

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[1] Sonnemann, G., & Vigon, B. (2011). *Global guidance principles for life cycle assessment LCA databases*. Paris: United Nations Environment Programme (UNEP).

1.4.3 LCA modelling concepts and definitions

The Model relies on a series of concepts used in LCA to keep information organized. The following concepts are referred to throughout the Model documentation:

- **Unit process**: Smallest divisible activity of a life cycle. It transforms quantities of inputs into quantities of outputs. It can use modeling parameters and background data.
- **Flow**: Material or energy stream entering (input) or leaving (output) a unit process. “Elementary flows” refer to exchanges between a unit process and the environment (i.e. extractions and emissions) while “intermediate flows” refer to exchanges between unit processes (e.g., electricity).
- **Life cycle stage**: Specific part of a life cycle (e.g., feedstock production). Life cycle stages are modelled by a collection of unit processes.
- **Fuel pathway**: Collection of unit processes, modeling parameters, and background data which represents the life cycle of a fuel from a given feedstock. In general LCA vocabulary, a fuel pathway is called a product system.
- **System process**: Process that contains the LCI of a group of unit processes.

Chapter 6 of the *Fuel LCA Model User Manual* provides detailed information about LCA concepts and definitions. The document also defines concepts that are part of the next chapter of the *Fuel LCA Model Methodology* such as functional unit, allocation procedures and life cycle impact assessment (LCIA) method.

Chapter 2: Goal and scope of the *Fuel LCA Model*

This chapter outlines the goal and scope of the Model, as well as the methodology that is consistent with all processes in the database. This includes the data collection methods, data quality indicators, LCI assessment methods, and limitations of the LCA methodology.

2.1 Goal

The goal of the Model is to allow the life cycle CI calculation of fuels and energy sources produced and used in Canada. The Model provides users with three components to calculate CIs: the *Fuel LCA Model Database*, *Fuel LCA Model Methodology*, and *Fuel LCA Model User Manual*.

The *Fuel LCA Model Database* consists of a data library of system processes of foundational CIs for fuel pathways, and configurable unit processes (configurable processes). While processes in the Data Library have been developed to model the life cycles of fuels produced in Canada, the Model also includes processes that model activities that occur outside Canada and that are needed to model fuels and energy sources produced and used in Canada. Fuel pathways are empty unit processes that allow users to model the life cycle of specific systems in the Canadian context, and configurable processes are partially completed unit processes that support fuel pathways.

The Model has been developed in conformity with ISO 14040 and 14044 requirements. As stated in ISO 14040, the CI results calculated by the Model are based on a relative approach, which means that they represent potential GHG emissions as opposed to actual GHG emissions. Therefore, the Model results should not be used to make direct comparative assertions for CIs or environmental impacts either outside of the scope of a specific program or without meeting the requirements of ISO 14040 and ISO

14044 standards. Programs that allow or require the use of the Model may have specific documentation on how to use the Model under the program.

2.2 Scope

2.2.1 Functional unit

A **functional unit** is defined as the quantified performance of a product system for use as a reference unit. This facilitates determination of reference flows for the systems being studied. There are two functional units for the fuel pathways in the Model. The first is 1 MJ of energy content based on the Higher Heating Value (HHV) delivered to the end user and used for its energy content. The energy content excludes fossil-based denaturant added to the fuel. The second is 1 kg of pure fuel at the fuel production gate.

CIs are expressed in grams of carbon dioxide (CO_2) equivalents (g CO_2e) per functional unit produced. For the energy-based functional unit, the Model does not take into consideration the efficiency of the combustion device. As such, a single combustion emission factor per fuel is applied to calculate the CI.

2.2.2 Data library of system processes

The *Fuel LCA Model Database* includes a data library of several hundred system processes which can be used when modelling CIs. These system processes were produced from the life cycle inventory (LCI) of multiple unit processes that were created as part of the development of the Model. System processes allow for the aggregation and simplification of multiple unit processes and increase accessibility of the Model. A visualization of the development of the Data Library is shown in **Figure 2**.

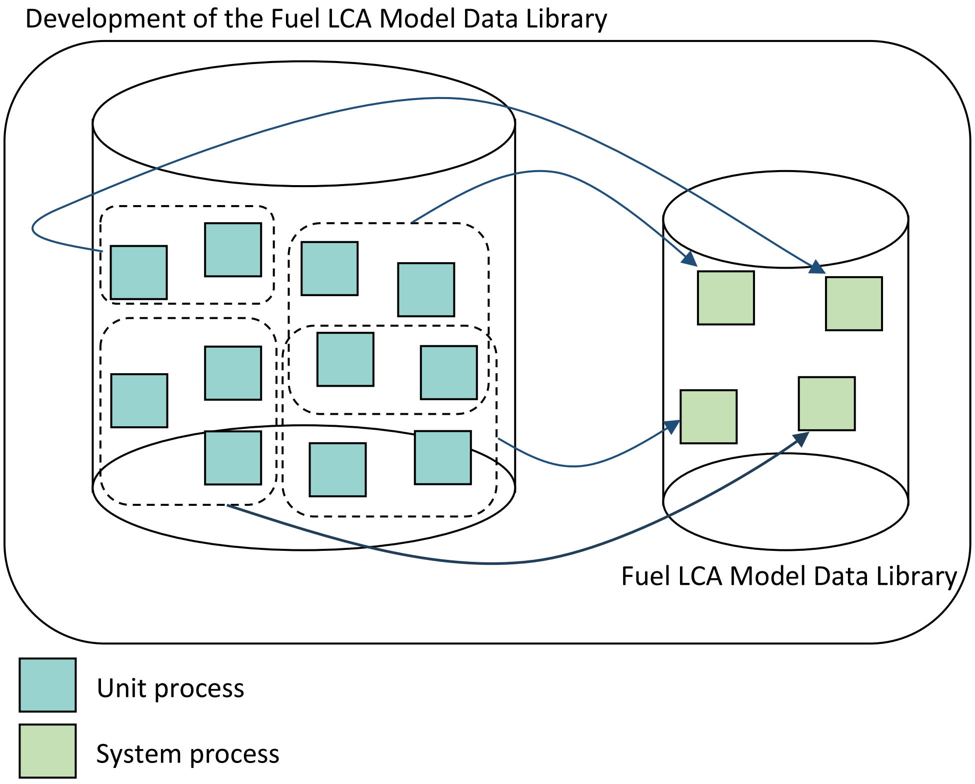

Figure 2: Visualization of the development of the *Model Data Library*

2.2.3 Fuel pathways and configurable processes

The Model contains unit processes that are structured to model various LCIF pathways. These pathways allow users to enter data and, using the system processes in the Data Library, generate a CI tailored to their modelling needs.

The Model also contains configurable processes that model certain activities. These unit processes are partially modelled and allow the user to replace certain flows with other flows representing their situation.

2.2.4 Geographical scope

The Model was developed to model the Canadian context. However, it also contains some international feedstock and electricity processes to better reflect the complex fuel production system in Canada. The modelling choices and data documentation for each type of international process are indicated in the specified sections of this document. The international processes included in the Data Library are listed below.

Feedstock

- Sugar cane for Brazil: Chapter 3.5.2

Grid electricity

- American states: Chapter 3.3.2
- Mexican national average: Chapter 3.3.2

- Brazilian national average: Chapter 3.3.2
- Argentinian national average: Chapter 3.3.2

Furthermore, some of the Canadian processes were developed such that they can be applied as proxy for similar processes occurring in other regions. For example, natural gas production was modelled using Canadian data and sorghum was modelled using American data, but both of these processes can be used regardless of geographical location. System processes that are applicable beyond the Canadian context are identified as such in the Data Library and are listed below, along with the chapter containing their documentation:

- Chemical inputs: Chapter 3.1
- Combustion emission factors: Chapter 3.2
- Technology-specific electricity: Chapter 3.3.4
- Other energy sources: Chapter 3.4
- Crops (excluding sugar cane): Chapter 3.5.2
- Residues: Chapter 3.5.3
- Other waste material: Chapter 3.5.4
- Fossil fuels: Chapter 3.6
- Renewable fuels: Chapter 3.7
- Transportation: Chapter 3.8

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 elementary flows in the analysis. The general system boundaries for the Model are defined by the five main life cycle stages, which are outlined in **Figure 3**.

The system boundary of each life cycle stage includes the life cycle GHG emissions associated with the use of feedstock, electricity inputs (both grid and onsite generation), fuel inputs, material inputs (e.g. chemicals), transportation processes, process emissions (e.g. venting and flaring), and other direct emissions. Excluded processes and cut-off criteria are presented in the following subsections.

Feedstock Production: resource acquisition (e.g., natural gas extraction, or soybean cultivation, etc.) and transformation (e.g., natural gas upgrading, or soybean oil extraction, etc.) into substances ready for transport to the fuel production plant.

Feedstock Transportation: transportation of feedstock from its last transformation activity to the fuel producer.

Fuel Production: (or fuel conversion) conversion of feedstock into fuel, including potential pre-processing of feedstock, and post-processing and upgrading of fuel to final fuel product.

Fuel Distribution: storage and handling of fuel, transport of finished fuel product to storage and to final user.

Fuel Combustion: combustion of the final fuel product by the end user.

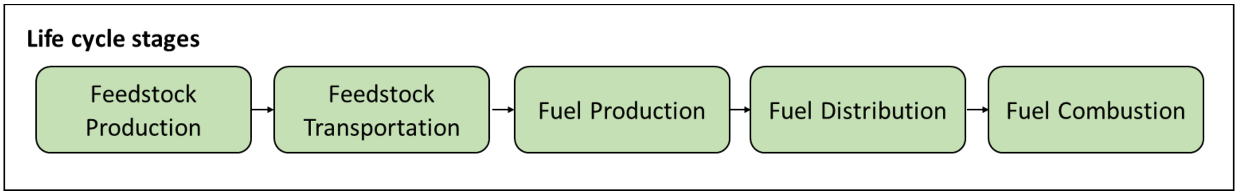

Figure 3: The five life cycle stages of LCIF in the Model

2.3.1 Excluded processes

The LCI in the Model prioritizes energy and material inputs that are part of the life cycle of a fuel, including the emissions associated with the production and the use of its inputs. From these inputs and emissions, only significant contributors to the CI of fuel are considered.

The following processes are excluded from the Model Database due to their negligible contribution or limitations such as lack of data, methods or high uncertainty.

- Construction and decommissioning of equipment and facilities
- 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
- Research and development activities
- Indirect activities associated with fuel production, such as marketing, accounting, commuting, and legal activities
- Indirect land use change

These exclusions have been applied consistently across the model, which limit the risk of bias and inconsistency between the different pathways.

2.3.2 Cut-off criteria

While the excluded processes represent explicit activities that are out of the scope of the Model, cut-off criteria are applied in LCA to the selection of processes or flows that are included in the study. The processes or flows below these cut-offs or thresholds may be excluded from the Model. Different types of criteria are used in LCA to decide which inputs and outputs are to be considered in the LCA, including mass, energy, and environmental significance. Definitions of 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)

As noted in ISO 14044, making the initial identification of inputs and outputs based on mass contribution alone may result in important inputs or outputs being omitted from the analysis. As such, energy and environmental significance have also been used as cut-off criteria.

In the Model, effort was made to include all the relevant flows associated with each process with the exception of the excluded processes listed in **Chapter 2.3.1**. During the completeness and sensitivity check, a 1% cut-off criteria has been applied on the environmental significance, as calculated by the impact assessment method. Cut-off criteria were applied at the individual unit process level.

Based on the cut-off criteria, the following additional processes are excluded from the Model Database:

- Ancillary materials (e.g. lubricants, cleaning agents, packaging, etc.)
- Water from municipal water supply systems or directly extracted from surface and underground sources

2.4 Data collection and data quality

This section outlines a set of data quality preferences established for the Model and which were applied during the modelling of the Data Library.

Data collection to develop the LCI was based on review and compilation of data from a wide range of sources including, government publications and statistics, industry publications and statistics, other fuel LCA modelling tools, and literature data for low carbon fuel systems with little or no current production in Canada. For ethanol and biodiesel production, several years of primary operating data were available for a large segment of Canadian ethanol and biodiesel producers, which were aggregated to protect the confidentiality.

The LCI data used in the fuel modelling is a mixture of data that is specific to Canadian systems and data from other jurisdictions that is considered adequately representative of Canada. When relevant, datasets from other jurisdictions were adapted to the Canadian context (e.g. replacing an electricity input with the Canadian grid mix process).

Due to the regional variability in a number of aspects in Canadian fuel production, the Model considers regional variation by providing some system processes defined at the regional (Eastern or Western Canada) or provincial level. The following regional factors, which could influence CI for LCIFs, were used in the Model, within the confines of the available data:

- Differences in fuel consumption in forest harvesting, sawmilling and other processing activities
- Background energy systems such as variations in electricity grids providing energy to fuel conversion processes

The following subsections present the data collection practices used in the development of the Model.

2.4.1 Data collection for system processes in the Data Library

The Model contains several different data sources for modelling the hundreds of system processes. The data quality levels and definitions considered for Model development are listed below.

High data quality

- Regionally specific and recent (less than 5 years)
- Based on measurements and published by official and verified sources (e.g. government statistics)
- Collected from more than 50% of sites in the region under study

Acceptable data quality

- Average from a larger region that include the region other study and no older than 10 years
- Based on measurements and published in scientific publications or by industry organization.
- Collected from a sample of sites

Lowest acceptable data quality

- Data or LCI extracted from recognized tools and initiatives (e.g. GREET)
- From a region different but representative of the region under study and no older than 15 years
- Measurement from a single site or expert estimate from qualified individual

Time and effort were invested to collect data that corresponds to the level of “high data quality”. When these types were not available, data corresponding to the “acceptable data quality” and “lowest acceptable data quality” levels were considered. Data sources that could not achieve the lowest acceptable data quality level were not included in the Model.

2.5 Data uncertainty

Data uncertainty was applied in the development of the Model to evaluate the quality of the data used for modelling the system processes of the Data Library. While data uncertainty was applied during model development, its results are not available in the Data Library.

To quantify data uncertainty, data quality indicators (DQI) were used to assess each flow using a data quality matrix approach. These scores were then used to assess uncertainties of the data and subsequently assess the uncertainty of the Model and the results with a Monte Carlo analysis.

When quantitative information about uncertainty was available (e.g. sample of data or standard deviation), the uncertainty was applied by specifying the dispersion parameters of the distribution type (for instance, uniform, lognormal or triangular distribution).

In instances where quantitative information about uncertainty was not directly available, the pedigree matrix provided by Weidema et al. (2013)[2] was used. It contains five types of DQI, each of which is assigned a score from 1 to 5 for the following parameters:

1. Reliability
2. Completeness
3. Temporal correlation
4. Geographical correlation
5. Further technological correlation

Based on these criteria, scores are assigned to the data and the linked pathways. These scores are then combined with basic uncertainty factors to develop squared geometric standard deviations for use in Monte Carlo analysis to determine the influence of data quality on the reliability of the results.

2.6 Co-product allocations

In cases where the studied system is a multifunctional process which generates more than one marketable product, the environmental burden related to that process may be distributed amongst the different outputs of the system (main product and co-products) using an allocation method. According to ISO 14044, the allocation approach 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 (e.g. mass or energy content) or other relationships (e.g. economic value) should be used.

The need to allocate environmental burdens between products and co-products arises at several points in the life cycle of several fuels, including:

- Canola and soybean meal co-products produced from vegetable oil extraction
- Animal feed and combined heat and power production co-products from ethanol production
- Agricultural and forest residues derived from primary cultivation and harvesting that are used to produce biofuels
- Extraction and processing of liquid and gaseous fossil fuels

The Model applies different allocation approaches, which are defined in the following sections.

2.6.1 Energy-based allocation

In the Model, energy content is the default allocation approach. In fuel production systems, energy content, also known and referred to as the HHV, is generally recognized as the most appropriate metric.

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[2] Weidema B P, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, Vadenbo C O, Wernet G., 2013. *Swiss Centre for Life Cycle Inventories Overview and methodology* (final) (v3) 3, 1(v3).

2.6.2 Mass-based allocation

The Model uses mass allocation for wood fibre and animal fat feedstock processes, as well as for the configurable process for oil from oilseeds.

2.6.3 System expansion

The system expansion approach involves taking into account the environmental burdens associated with the substituted product of a co-product produced at the fuel production facility. The environmental burdens associated with this substituted product are subtracted from the CI of the product system under study. For example, a fuel production plant can generate excess electricity as a co-product which can then be used on site or exported to the grid. With a system expansion approach, it is assumed that the excess electricity will "displace" the environmental burdens associated with grid electricity (which represents the substituted product).

System expansion is used in the Model for excess electricity and steam produced at the fuel production facility. In the case of excess electricity, the Model includes a list of processes for excess electricity representing different regional grid mixes and a single process for excess steam.

System expansion can also be applied when a waste material is used as feedstock for LCIF production and results in real methane reductions. In this case, the system boundary around the waste material for fuel production should be expanded to include the emission differential between using the waste material for fuel production and a baseline scenario that would have occurred if the waste material was not used for fuel production.

2.6.4 Cut-off allocation

Some of the feedstock processes in the Data Library represent wastes from other industries such as used cooking oil (transformed into yellow grease) from restaurants and animal fats from slaughterhouse. This is a case of waste recycling. The Model applies the "cut-off" allocation approach to waste recycling. Under the "cut-off" allocation 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. Consequently, waste products used as feedstock are represented in the Model by empty unit processes (zero CI).

2.7 Greenhouse gases, biogenic carbon and land use change

In accordance with the scope of the *National Inventory Report* (NIR), the Model LCI includes CO_2, methane (CH_4), nitrous oxide (N_2O), halocarbons and related components, but excludes near-term climate forcers (e.g. CO, NOx, VOC, black carbon) and other forcing factors (e.g. albedo effects). Biogenic CO_2 emissions associated with LCIF combustion are set to zero in the LCI of the Model. In line with the Intergovernmental Panel on Climate Change (IPCC), it is assumed that the biogenic CO_2 emissions are balanced by carbon uptake prior to harvest.[3]

Biogenic CO_2 emissions from changes in land management practices are taken into account in the modelling of crops: changes in crop productivity and crop residue carbon inputs, changes in tillage

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[3] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. Kanagawa (JP): Institute for Global Environmental Studies.

practices and changes in summerfallow area[4]. Carbon emissions from changes in the proportion of annual and perennial crops are not considered; indirect land use changes are excluded from the Model.

Biogenic CO_2 and CH_4 emissions from land use change for hydro reservoirs are included in the scope of the Model.

Finally, it is generally 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 (other than the ones mentioned above).

2.8 Life cycle impact assessment methods

Life cycle impact assessment (LCIA) methods are used in LCA to convert LCI data (environmental emissions and feedstock extractions) into a set of environmental impacts using impact factors.

In the Model, there are two LCIA methods available for calculation. These methods employ impact factors that use global warming potentials (GWP) for a 100-year time horizon. The 100-year time horizon is the impact factor most-widely applied in CI studies, which facilitates ease of comparison to other study results. The two LCIA methods available in the Model use the GWP-100 values sourced from the IPCC's Fifth Assessment Report (AR5)[5] and Sixth Assessment Report (AR6)[6] respectively. For both LCIA methods the near-term climate forcers and climate-carbon cycle feedbacks are not considered for consistency with the NIR and other GHG accounting initiatives in Canada. The CIs resulting from the LCIA method are expressed in grams of CO_2eper MJ of HHV energy. It should be noted that the GWP of the IPCC AR6 were used for flows of the Data Library of the Model Database expressed in CO2e.

Table 1 provides a summary of the GWP for the main GHGs for both LCIA methods. A complete list of GHGs with their associated GWP in the two LCIA methods are available in the Model Database in their respective *Impact categories* under the *Indicators and parameters* section in openLCA.

In remaining consistent with the Government of Canada's policy on biogenic carbon, as shown in Canada's NIR (2023), the GWP for uptake of carbon during the biomass growth and emissions of biogenic carbon from combustion of low carbon fuels are not reported. The assumption is that biogenic CO_2 emissions associated with LCIF combustion are balanced by carbon uptake prior to their harvest. The Model considers that CO_2 emissions or atmospheric CO_2 uptake from changes in soil organic carbon (SOC) due to land management practices have the same GWP as fossil CO_2. It is considered that these emissions or uptake have a lasting effect on the concentration of GHG in the atmosphere.

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[4] Biogenic emission from changes in summerfallow area are included for sorghum only.

[5] Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[6] Smith, C., Z.R.J. Nicholls, K. Armour, W. Collins, P. Forster, M. Meinshausen, M.D. Palmer, and M. Watanabe, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)].

Furthermore, the Model does not take in consideration the temporal profile of uptake and emissions of biogenic carbon (also called the carbon debt). In other words, the capture of carbon during forest biomass growth will fully compensate carbon emissions from biomass combustion independently of the time delay between these two events. The temporal aspect is not included to be consistent with the GHG accounting rules in other governmental programs and initiatives.

Table 1. Select characterization factors for calculating carbon intensities using IPCC AR5 and AR6 GWP-100

Greenhouse gas	**FuelLCAModelLCIA_AR5 GWP-100 (gCO2e/g)**	**FuelLCAModelLCIA_AR6 GWP-100 (gCO2e/g)**
CO_2	1	1
CO_2 (biogenic)	0	0
CO_2 (land use change)	1	1
CH_4 (fossil)	30	29.8
CH_4 (biogenic)	28	27.9
N_2O	265	273
Sulfur hexafluoride	23,500	24,300

2.9 Limitations of the *Fuel LCA Model*

The Model is based on current data and information regarding Canadian production systems, and some foreign systems. As such, the Model does not include information regarding future technologies or policy implications on the Canadian energy sector.

Given that the scope of the Model is limited to the calculation of CI, other environmental indicators are not covered.

Since the Model is based primarily on publicly available data, the processes included represent generic or average practices. This limitation is partly mitigated through the inclusion of the fuel pathways, which allow users to input facility-specific data.

Chapter 3: *Fuel LCA Model* Data Library

As mentioned, the Model Database is composed of multiple "building blocks" that can be used to model fuel life cycles and calculate CIs. This chapter presents the modelling approach, functional unit, modelling assumptions and data sources used to model system processes in the data library.

3.1 Chemical inputs

3.1.1 Chemicals

Modelling approach for chemicals

Chemicals used throughout the production processes of LCIF pathways notably include enzymes, acids, fertilizers, and catalysts. The functional unit for each chemical is 1 kg of product, unless otherwise specified. The methodology for determining the CI for each of these chemicals included in the Model is described below, and the methodology used depends on Canadian data availability.

The following processes are modelled using the 2018 *Greenhouse gases, Regulated Emissions, and Energy use in Technologies* (GREET) model life cycle emission factors.

- Acetic acid (CH3COOH)
- Alpha amylase
- Calcium carbonate (CaCO3)
- Lime (CaO)
- Cellulase
- Cellulase protein
- Citric acid (C6H8O7)
- Corn steep liquor
- Gluco amylase
- Glucose
- Hexane (n-hexane)
- Hydrochloric acid (HCl)
- Methanol (CH3OH), from natural gas
- Nitrogen gas (N), gaseous, from natural gas
- Potassium hydroxide (KOH)
- Sodium hydroxide (NaOH)
- Sodium methoxide (CH3ONa)[7]
- Yeast
- Yeast extract

The following processes are modeled using the GREET 2022 model process energy, material inputs, and process emissions. The functional units are on a mass of product basis, unless otherwise specified.

- Ammonium nitrate (NH4NO3) [8]
- Ammonium sulfate ((NH4)2SO4)

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[7] In the specific case of sodium methylate (sodium methoxide), as a result of a lack of data within the GREET 2018 model, emissions values were determined using those of methanol (from natural gas) and the stoichiometry of the reaction producing sodium methoxide from methanol.

[8] Functional unit: 1 kg of nitrogen in ammonium nitrate

- Monoammonium phosphate (NH4H2PO4)[9]
- Monoammonium phosphate (NH4H2PO4), as N
- Monoammonium phosphate (NH4H2PO4), as P2O5
- Nitric acid (HNO3)
- Diammonium phosphate ((NH4)2HPO4))[10]
- Diammonium phosphate ((NH4)2HPO4)), as N
- Diammonium phosphate ((NH4)2HPO4)), as P2O5
- Phosphoric acid (H3PO4)
- Sulfuric acid (H2SO4)
- Urea-Ammonium nitrate (UAN)[11]

It should be noted that elemental sulfur used in the sulfuric acid production carries no emissions since it is a waste product from another industry.

Moreover, in the case of monoammonium phosphate (MAP) and diammonium phosphate (DAP), the processes for both allocated nutrient categories belonging to a multinutrient fertilizer (N and P_2O_5) must always be used together. The user must ensure that the quantities of both components of the multinutrient fertilizers are correctly reported.

The CI of the following chemical processes are based on the Canadian production data (feedstock and energy requirements) collected from Greenhouse Gases Reporting Program (GHGRP) for the year 2019-2020-2021-2022:

- Ammonia from SMR (NH3)
- Urea (CH4N2O)

The modeling of ammonia and urea considers that ammonia from steam methane reforming (SMR) and urea are co-products. Urea production combines two molecules of ammonia with one molecule of carbon dioxide to form urea and water in solution. With this dual process, a portion of the CO2 is recovered by the urea process, emissions that would otherwise be emitted to the atmosphere. A feedstock ratio of 0.567 kg NH3/kg urea is used to calculate the mass balance of the net ammonia production (stoichiometric mass ratio for $2NH_3 + CO_2 \rightarrow CH_4N_2O + H_2O$). Allocation procedures based on nitrogen content was used for the ammonia and urea co-products. The nitrogen content used were 82.2% and 46.6% for ammonia and urea respectively.

The modelling of the ammonia and urea processes uses Canadian data from the Greenhouse Gas Reporting Program (GHGRP) - Facility Greenhouse Gas (GHG) Data. A four-year combined average, from 2019 to 2022, for production, natural gas feedstock and energy requirements data was used. Plant activities considered include flaring, on-site transportation, steam generation, and other stationary combustion. Only plants that produce ammonia from steam methane reforming were used.

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[9] MAP is a multi-nutrient fertilizer with system processes available on both a per kg of product basis and a per kg of nutrient basis (N and P_2O_5).

[10] DAP is a multi-nutrient fertilizer with system processes available on both a per kg of product basis and a per kg of nutrient basis (N and P_2O_5).

[11] Functional unit: 1 kg of nitrogen in UAN

Note that hydrogen is also included in the Chemical folder in the Data Library, but this process is documented in **Chapter 3.1.3.**

Geographical scope for chemicals

The processes are modeled using Canadian and American data. They can be used to represent the production in North America.

Allocation for chemicals

For Ammonia from SMR and Urea: Allocation based on nitrogen nutrient content was used for the ammonia and urea co-products in the background modelling. The nitrogen content used were 82.2% and 46.6% for ammonia and urea respectively.

For MAP and DAP: For the per-mass of nutrient basis processes, energy requirements, taken from GREET 2022, are allocated to specific nutrient based on factors taken from Ecoinvent (2007), and material inputs are entirely allocated to the nutrient category they represent.

No allocation procedures were performed for the other chemicals.

Data sources for chemicals

- Environment and Climate Change Canada. Greenhouse Gas Reporting Program (GHGRP) - Facility Greenhouse Gas (GHG) Data – Ammonia production (2019-2020-2021-2022).
- The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2018). Argonne GREET Model (anl.gov)
- The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2022). Argonne GREET Model (anl.gov)
- Thomas Nemecek & Thomas Kägi. Agrosope Rechenholtz Tänikon Research Station (ART). Life Cycle Inventories of Agricultural Production Systems (data v2.0 [2007]). Ecoinvent Report No. 15. December 2007. (Ecoinvent 2007)

3.1.2 Agrochemicals

Modelling approach for agrochemicals

The CI values for synthetic fertilizers were determined using two different methods depending on the fertilizer nutrient types (nitrogen (N), phosphorus (P), potassium (K) and sulphur (S)). The LCI for N, P and K fertilizers were based on average Canadian CIs calculated with AR5 GWP and published in a 2016 study from Cheminfo Services Inc. referenced in the 2017 carbon footprint reports for Canadian crops from the Canadian Roundtable for Sustainable Crops (CRSC) (Cheminfo, 2016), taking into account the stoichiometry of products and nutrients. The CI for S-based fertilizers was considered to be zero because the most common S fertilizer used in Canada (ammonium sulfate) is produced as a by-product (waste) in mining and smelting operations. Therefore, no emissions were associated with S fertilizer production.

In the absence of detailed Canadian data on the shares of each type of pesticide used in Canada on a given crop, the average CI for pesticide was calculated as the average of the GREET 2018 emission factors for five primary pesticides in widespread use in Canada (atrazine, metolachlor, acetolachlor, cyanazine, and insecticides) for the relevant crops.

Geographical scope for agrochemicals

There is a lack of Canadian-specific LCI data on agrochemicals. For this reason, foreign data was used. It is assumed that processes do not vary between regions. The processes can be used regardless of geographical location.

Allocation for agrochemicals

No allocation was performed for agrochemicals modelling.

Data sources for agrochemicals

Emission factors for pesticides were taken from the GREET 2018 model. Fertilizers were modeled based on the CI values calculated taken from the 2016 study from Cheminfo Services Inc. referenced in the 2017 carbon footprint reports for Canadian crops from the CRSC. The data sources are summarized below.

Fertilizers, products CIs:

- Cheminfo. (2016). Carbon Footprints for Canadian Crops: Canadian Fertilizer Production Data Final Report. Cheminfo Services.

Pesticides, active ingredient CIs:

- Argonne National Lab. (2018). GREET.

3.1.3 Hydrogen

The Model includes a system process that models the production of hydrogen from steam methane reforming (SMR) when hydrogen is used as material or fuel input. While the Data library only includes hydrogen from SMR, users can use existing system processes in the Data library to model hydrogen production from other sources and production methods with a fuel pathway (**0**). The modelling of SMR hydrogen production in the Model is based on a techno-economic analysis completed by the International Energy Agency (IEAGHG 2017). Inputs and outputs needed to model SMR hydrogen production are based on this analysis (e.g. amounts of natural gas needed as feedstock and fuel, as well as amounts of hydrogen and excess electricity produced). Energy requirements for the geological storage of the produced hydrogen is modelled based on a study by Ramsden (Ramsden et al. 2013).

Modelling approach for hydrogen

In the SMR process, CH_4 from fossil natural gas reacts with steam in the presence of a catalyst to produce hydrogen, carbon monoxide (CO), and CO_2. In the next step, CO and steam are reacted using a catalyst to produce CO_2 and more hydrogen, followed by pressure-swing adsorption during which CO_2 and other impurities are removed to produce pure hydrogen.

The process begins with the production and transmission of natural gas to the hydrogen production plant via gas pipeline. The process ends with the production of 1 MJ of hydrogen at the plant gate, including geological storage. The process includes process emissions (i.e. CO_2), while CH_4 and N_2O emissions from the hydrogen SMR process are considered negligible. Hydrogen leaks during production are assumed to be negligible as well and are therefore excluded from the process. The hydrogen production includes electricity export to the grid produced from excess steam at an onsite cogeneration plant. **Figure 4** displays the processing overview for the production of hydrogen from SMR. Modelling for the extraction of natural gas is described in **Chapter 3.6.2**. The production process produces a functional unit of 1 MJ HHV of hydrogen.

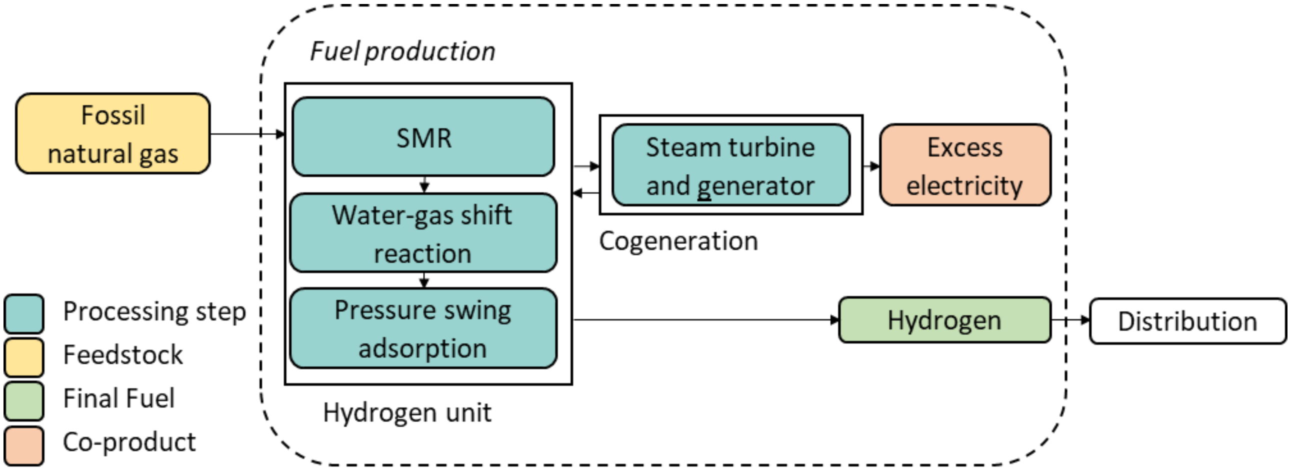

Figure 4: Processing overview for the production of hydrogen from SMR

Geographical scope for hydrogen

The SMR conversion process was modelled based on a theoretical state-of-the-art SMR plant producing 100,000 Nm^3 /h of hydrogen using natural gas as feedstock and fuel, as assessed in the IEAGHG (2017) study. The plant is assumed to operate as a standalone facility without integration to other industrial complexes. This theoretical hydrogen production plant is used as a proxy to model Canadian hydrogen conversion from SMR. This assumes that processes do not vary between regions. The process can be used regardless of geographical location.

Allocation for hydrogen

Excess electricity is treated with a system expansion approach. The excess electricity is assumed to be exported to the grid and a credit corresponding to the CI of the Canadian average grid mix is attributed to the hydrogen production system. **Chapter 3.3.3** provides additional information about the modelling approach for excess electricity exported to the grid.

Data sources for hydrogen

The conversion of fossil natural gas to hydrogen using SMR was modelled using data compiled by the IEAGHG, specifically amounts of natural gas consumption and excess electricity export expected from a 100,000 Nm^3/ h hydrogen plant. Because there are few large-scale operating facilities that produce hydrogen, the IEAGHG data is based on a theoretical base case production scenario. The main data sources used in modelling the conversion of hydrogen from natural gas are listed below.

- IEAGHG. (2017). Techno-Economic Evaluation of SMR Based Standalone (Merchant) Plant with CCS. 2017/02, February. 2017.
- Ramsden, T., Ruth, M., Diakov, V., Laffen, M., & Timbario, T. A. (2013). Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios.

- Sun P., Young B., Elgowainy A., Lu Z., Wang M., Morelli B., and Hawkins T. (2019). Criteria Air Pollutants and Greenhouse Gas Emissions from Hydrogen Production in U.S. Steam Methane Reforming Facilities. Environmental Science & Technology 2019 53 (12), 7103-7113. DOI: 10.1021/acs.est.8b06197.

3.1.4 Predefined chemical mixes

The Model contains three types of predefined chemical mixes to represent the chemicals used in the production of three types of fuels: conventional bioethanol, cellulosic ethanol, and biodiesel. The functional unit for each chemical mix is the quantity of chemicals needed to produce 1 MJ (based on HHV) of the specified LCIF.

Modelling approach for predefined chemical mix for conventional bioethanol production

The predefined chemical mix for conventional bioethanol production was modelled using Canadian production data from the Complementary Environmental Performance Reports (CEPR). These reports were compiled by Natural Resources Canada (NRCan) as part of NRCan's ecoENERGY for Biofuels Program. The predefined chemical mix CI for bioethanol is a weighted average of the CI of the chemicals used for bioethanol from corn and from wheat. The process scope includes starch extraction, liquefaction and saccarification, fermentation, and distillation and drying. The chemicals considered are gluco amylase, ammonia, urea, sodium hydroxide, alpha amylase, sulfuric acid, and yeast. The modelling for these chemical inputs is described in **Chapter 3.1.1**.

Three types of data exclusions were applied to the conventional bioethanol production facilities:

1. General plant-year exclusions
    a) Facilities-years with a mass balance out of the range [0.75, 1.25].
    b) Facilities-years for which the blending feedstock types is high (i.e. percentage of input feedstock inside the range]40%, 50%[)
    c) Facilities-years for which the production rate (L biodiesel/tonne feedstock) is out of the range [arithmetic average over all facilities and all years - 2*standard deviation, arithmetic average over all facilities and all years + 2*standard deviation].
2. Specific parameters exclusions
    a) Flow amounts were individually excluded when out of range [arithmetic average over all facilities and all years - 2*standard deviation, arithmetic average over all facilities and all years + 2*standard deviation]
3. Manual exclusions of plant
    a) All flow amounts were excluded for a facility-year considered non-representative (the facility was starting its production at a very low capacity).

As there is no wet mill facility in Canada, the process is representative of dry mills. There is no flow for denaturant input and sodium hypochlorite in the Model Database. The reported flows are negligible and therefore are not considered in the modeling.

Geographical scope for predefined chemical mix for conventional bioethanol production

The CEPR data was compiled to model a single process for chemical use for bioethanol production. This assumes that the production process is the same across provinces. The process can be used regardless of geographical location.

Allocation for predefined chemical mix for conventional bioethanol production

No allocation was performed.

Data sources for predefined chemical mix for conventional bioethanol production

- Complementary environmental performance reports (CEPR) (2009-2017). Natural Resources Canada (NRCan) as part of NRCan's ecoENERGY for Biofuels Program. Biodiesel and bioethanol.

Modelling approach for predefined chemical mix for cellulosic bioethanol production

The predefined chemical mix for cellulosic bioethanol production was determined based on data on cellulosic bioethanol production from wheat straw and corn stover. The production processes modelled included enzymatic pre-treatment, C5 / C6 sugar fermentation, and distillation. The chemical inputs that were considered in the bioethanol production process were corn steep liquor, cellulase, calcium carbonate, sodium hydroxide, diammonium phosphate, yeast, ammonia, and sulfuric acid. The modelling for these chemical inputs is available in **Chapter 3.1.1**. The results were then used to create the predefined chemical mix for cellulosic bioethanol.

Geographical scope for predefined chemical mix for cellulosic bioethanol production

The cellulosic bioethanol conversion process was modelled based on a United States of America (U.S.) literature review. The data was compiled to model a single national average approach for cellulosic ethanol conversion from corn stover. This assumes that the conversion process is the same across provinces. The process can be used regardless of geographical location.

Allocation for predefined chemical mix for cellulosic bioethanol production

The allocation of burdens of the chemicals and other inputs in the cellulosic bioethanol production process is based on energy content.

Data sources for predefined chemical mix for cellulosic bioethanol production

The data used to model the production of cellulosic bioethanol for the CI determination of the predefined chemical mix was gathered from a 2011 study by the National Renewable Energy Laboratory (Humbird, et al., 2011). Excluding feedstock, data for inputs to each step in the production process were obtained from the GREET model (Lee, Han, & Wang, 2016) and the Environmental Resource Letters from Wang, Han, Dunn, Cai, & Elgowainy, 2012. The conversion of sugars to bioethanol for corn was considered with the same efficiency as that from wheat, however corn stover was modelled to have a higher sugar yield than wheat straw.

The main data sources used in modelling are listed below.

- Humbird, D., Davis, R., Tao, L., Hsu, D., Aden, A., Schoen, P., … Duedgeon, D. (2011). Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis. Golden, CO: National Renewable Energy Laboratory.
- Lee, U., Han, J., & Wang, M. (2016, October). Argonne National Laboratories. Retrieved from Well-to-Wheels Analysis of Compressed Natural Gas and Ethanol from Municipal Solid Waste.
- Wang, M., Han, J., Dunn, J., Cai, H., & Elgowainy, A. (2012). Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environmental Resource Letters, 7(4), 13.

Modelling approach for predefined chemical mix for biodiesel production

The predefined chemical mix CI for biodiesel is a weighted average of the CI of the chemicals used for biodiesel production from vegetable oils (soybean, canola and camelina) and from high free fatty acid (FFA) feedstocks (animal fats, used cooking oil (UCO) and corn oil). The predefined chemical mix CI for biodiesel production was modeled using Canadian production data from the Complementary Environmental Performance Reports (CEPR). These reports were compiled by Natural Resources Canada (NRCan) as part of NRCan's ecoENERGY for Biofuels Program.

The processes used for the chemical use modelling include starch extraction, liquefaction and saccarification, fermentation, and distillation and drying. The chemicals used in the modelling are potassium hydroxide, sulfuric acid, sodium methoxide, acetic acid, and sodium hydroxide. The modelling for these chemical inputs is described in **Chapter 3.1.1**.

The modelling for oil extraction is available in **Chapter 4.2.5**. The modelling for animal fats production is available in **Chapter 3.5.1**. The modelling for UCO and yellow grease is available in **Chapter 3.5.6**. For biodiesel produced from canola oil, the conversion process and chemical inputs modelling relied on Canadian production data collected and averaged from 2009-2017, provided by the CEPR. Methanol was not included in the predefined chemical mix so that it can be modelled by the user.

The same data exclusions as conventional bioethanol was used for biodiesel. There is also no flow for trysil input in the Model Database. The reported flow is negligible and therefore are not considered in the modeling.

Geographical scope for predefined chemical mix for biodiesel production

The CEPR data was compiled to model a single process for chemical use for biodiesel production. This assumes that the production process is the same across provinces. The process can be used regardless of geographical location.

Allocation for predefined chemical mix for biodiesel production

No allocation was performed.

Data sources for predefined chemical mix for biodiesel production

- Complementary environmental performance reports (CEPR) (2009-2017). Natural Resources Canada (NRCan) as part of NRCan's ecoENERGY for Biofuels Program. Biodiesel and bioethanol.

3.2 Combustion emission factors

The Model Data library includes several processes that model solely fuel combustion; these processes do not include the life cycle emissions related to the production of each fuel. The Data library contains two folders: combustion from biomass feedstock and combustion from non-biomass feedstock.

Modelling approach for combustion by fuel type

Below is a list of the modelling approach taken for the combustion of each fuel in the Model and includes main data sources. As hydrogen combustion does not release GHGs, no emissions are included in the combustion modelling.

For most renewable fuels included below the emission factors from the combustion of an equivalent fossil-based fuel have been used as a proxy. Hence, the approach explained in **Chapter 3.6.2** for calculating the combustion emission factors for fossil fuels also applies to these fuels.

The same emission factors were used for LCIF made from biomass and non-biomass feedstock. However, the carbon emission factors (i.e. CO_2 and CH_4) from the combustion of fuel made from biomass-based feedstock are considered as biogenic emissions. In accordance with the Government of Canada's policy on biogenic carbon, the biogenic CO_2 emissions is not included in the CI calculations in the Model and biogenic CH_4 emissions have a different impact factor than fossil CH_4 emissions. If a fuel is made from non-biomass feedstock, the carbon content is then considered non-biogenic and the CO_2 and CH_4 emissions from the combustion are accounted as fossil emissions. Please refer to **Chapters 2.7** and **2.8** for further explanations about biogenic and fossil emissions accounting in the Model.

Bioethanol: Emission factors for CH_4 and N_2O for fossil-based gasoline combustion from the NIR are used as a proxy. Only the neat (unblended) portion of the fuel is considered.

Biodiesel: The carbon content of the fuel linked to the used of methanol is considered as fossil and estimated based on stoichiometric calculations (however, emissions of fossil CH4 associated with methanol are neglected).

Biogas: Emission factors for natural gas combustion from the NIR are used as a proxy assuming that on a MJ basis emissions will be similar.

Hydrogen: As hydrogen combustion does not release GHGs, there are no emissions from combustion based on the scope of the Model.

Natural gas: Emission factors for the marketable fossil-based natural gas combustion from the NIR are used.

Propane: Emission factors for propane combustion from the NIR are used.

Renewable Diesel: Emission factors for fossil-based diesel combustion from the NIR are used as a proxy.

Renewable Gasoline: Emission factors for fossil-based gasoline combustion from the NIR are used as a proxy.

Renewable Naphtha: Emission factors for fossil-based kerosene combustion from the NIR are used as a proxy.

Renewable Natural Gas (RNG): Emission factors for fossil-based natural gas combustion from the NIR used as a proxy. However, per MJ emission factors have been calculated using the RNG HHV.

Renewable Propane: Emission factors for fossil-based propane combustion from the NIR are used as a proxy.

Sustainable Aviation Fuel: Emission factors for fossil-based aviation turbo fuel combustion from the NIR are used as a proxy.

Data sources for combustion by fuel type

- Data source: Government of Canada. (2018). National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada.

3.3 Electricity

3.3.1 Scope of electricity modelling

The Model contains several system processes that model electricity generation and transmission processes. These processes are divided into three categories:

- Grid mix processes representing Canada, the U.S., Mexico, Brazil, and Argentina
- Processes for displaced electricity production associated with excess electricity exported to the grid
- Technology-specific processes for electricity generation (e.g. “hydropower, reservoir”)

The modelling and boundaries for each category is described in the following subsections.

3.3.2 Modelling approach for grid electricity

The available grid mix processes for Canada, the U.S., Mexico, Brazil, and Argentina are shown below.

Canada:

- Canadian provinces and territories
- Canadian national average

United States:

- U.S. states
- U.S. national average

Mexico, Brazil, Argentina:

- National average for each country

The scope for these processes includes the following:

- Combustion emissions from fuel used for electricity generation
- Cradle-to-gate GHG emissions for fossil fuels and uranium used for electricity generation
- Reservoir emissions related to hydroelectricity
- Electricity losses from electricity transmission and distribution
- SF_6 emissions produced from equipment used in electricity transmission and distribution

In addition to the exclusions mentioned in **Chapter 2.3.1**, inter-provincial (or inter-state) and international trade are not considered in the modelling of these processes.

The functional unit for electricity grid mix processes is 1 kWh of electricity produced and distributed from the grid. No allocation is required for the modelling of electricity production.

Canadian grid mixes

The Canadian grid electricity processes were modelled using the 2023 NIR, using the 2021 reference year. Provincial and national direct emissions for the grid from the NIR were used to model the provincial and national grid processes. The NIR presents annual data on electricity generation by fuel type and direct combustion emissions for each province and territory, including data on electricity losses and SF_6 emissions associated with electricity transmission and distribution. The electricity CIs are calculated by dividing the GHG emissions by the net production of electricity.

Reservoir emissions are based on net emissions over 100 years as estimated from the G-res model and published in table 5 of Levasseur et al. (2021). The estimations are for Quebec reservoirs but they are used as proxy for all reservoirs in Canada. The fraction of hydroelectricity in grid mixes is directly provided by the NIR. The fraction of hydroelectricity that is from reservoirs versus run-of-water are taken from the *Canadian Analytical Framework for the Environmental Evaluation of Electricity* (CAFE3), an internal Environment and Climate Change Canada (ECCC) LCA model for electricity generation. It was developed by the International Reference Centre for the Life Cycle of Products, Processes and Services (CIRAIG) and ECCC. CAFE3 uses data from various sources, including the LCI database Ecoinvent v3.6 (e.g. to model the cradle-to-gate emissions of materials), National Energy Board (NEB), Statistics Canada, National Pollutant Release Inventory and US EPA, augmented with data from the CIRAIG. Missing data are completed with literature sources and proxies.

The national and provincial fractions of hydroelectricity that is from reservoirs, as provided by CAFE3, are shown in **Table 2**. Note that these values were not vetted by provinces or utilities.

Table 2: Fractions of hydroelectricity generation that are from reservoirs, by region

Region	Fraction
Canada	0.78
Alberta	0.66
British Columbia	0.95
Manitoba	0.998
New Brunswick	0.91
Newfoundland and Labrador	0.97
Nova Scotia	0.56
Northwest Territories	0.00
Nunavut	0.00
Ontario	0.867
Prince Edward Island	0.00
Quebec	0.629
Saskatchewan	0.97
Yukon	0.00

Fuel amounts used per kWh on the grid are calculated using the grid mix composition and heat rates for fuel consumption (in MJ of fuel per kWh of electricity output). The calculated fuel amounts take into consideration electricity losses based on NIR.

The main source of information for the grid mix composition is the NIR 2023. However, provided that some of the fuels used for electricity generation listed in the NIR are aggregated, additional data sources from Statistics Canada were used to identify the specific fuels used to generate electricity.

Heat rates for power plants consuming fossil fuels are determined using Statistics Canada Fuel usage by technology (Statistics Canada Table 25-10-0029-01) and Statistics Canada Fossil fuel energy generation (Statistics Canada Table 25-10-0028-01) data. In order to minimize the variability in calculated heat rates at the provincial level due to statistical limitations, the Canadian average heat rate (expressed in MJ/kWh) was used for all provinces and territories. The heat rate used for nuclear facilities was taken from CAFE3, but its source material originates from a proprietary database and as such its value cannot be included in this document. Unit process inputs are modelled to represent the MJ of fuel feedstock per kWh electricity consumed.

The sources used to model the Canadian grid mixes are listed below.

Electricity production data and grid composition:

- Government of Canada. (2023). National Inventory Report 1990-2021: Greenhouse Gas Sources and Sinks in Canada

Coal disaggregation data (lignite, bituminous, and sub-bituminous):

- Statistics Canada. Table 25-10-0019-01: “Electricity from fuels, annual generation by electric utility thermal plants”

Other fuels disaggregation data (diesel, light fuel oil, heavy fuel oil):

- Statistics Canada. Table 25-10-0028-01: “Electricity generated from fossil fuels, annual”.

Fuel usage by technology:

- Statistics Canada. Table 25-10-0029-01: “Supply and demand of primary and secondary energy in terajoules, annual”

Nuclear heat rate and hydro reservoir fractions:

- Environment and Climate Change Canada. Canadian Analytical Framework for the Environmental Evaluation of Electricity (CAFE3)

Hydro-reservoir biogenic emissions factors:

- Levasseur, A., S. Mercier-Blais, Y. T. Prairie, A. Tremblay, and C. Turpin. 2021. Improving the Accuracy of Electricity Carbon Footprint: Estimation of Hydroelectric Reservoir Greenhouse Gas Emissions. Renewable and Sustainable Energy Reviews 136 (February): 110433

American grid mixes

The American grid electricity processes were modelled using eGrid 2021 data, published in 2023. State-level emission factors were directly taken from modelled eGrid for the year 2021.

The main methodologies and assumptions about the calculated heat rate values (in MJ of fuel per kWh of electricity output) for coal and oil are listed below.

Coal

- State-specific heat rate values (in MJ/kWh) were calculated.
- Four additional coal types that are covered in eGrid which are not included in the Fuel LCA Model: coke-oven gas (<1% of coal power), refined coal (20%), coal-derived synthetic gas (<1%) and waste coal (<1%). The amounts from eGrid for these coal types were therefore reallocated to the coal types covered in the Fuel LCA Model (lignite, bituminous and sub-bituminous) in the proportion in which these latter are used in the state for power production.

Oil

- The national average heat rate is used rather than state-specific heat rates due to high variability between states.
- While waste oil use for electricity generation is significant in Hawaii and Alaska, it is not accounted for in the CI calculation as it is assumed that the cradle-to-gate impacts of bringing the waste oil to power plants is negligible. Combustion emissions from burning waste oil are included in the direct emission data from eGrid.

SF_6 emissions are taken from the US National Inventory Report Table 2-11 and scaled per kWh using eGrid data. All emissions and feedstock amounts were scaled to account for losses in transmission and distribution using 2021 eGrid data on losses. A national U.S. process was developed by weighting State-level processes according to the respective State's net annual net generation.

Feedstock amounts per kWh were calculated using plant-level fuel consumption data, per state, in eGrid. Reservoir emissions are based on the world average factors of 85g CO_2/kWh and 3g CH_4/kWh provided in Hertwitch, 2013. An estimation of the ratio of hydroelectricity from reservoir to run-of-river of 1:5 was applied, based on Itten et al, 2012.

The state fractions of reservoir hydroelectricity are shown in **Table 3.** These values were not vetted by states or utilities.

Table 3: Fractions of hydroelectricity generation that are from reservoirs, by state

State	Fraction
Alabama	0.0161
Alaska	0.0512
Arizona	0.0112
Arkansas	0.0135
California	0.0146
Colorado	0.0055
Connecticut	0.00217
Delaware	0
District of Columbia	0
Florida	0.000204
Georgia	0.00568
Hawaii	0.0025
Idaho	0.095
Illinois	0.000142
Indiana	0.000822
Iowa	0.00289
Kansas	0.000106
Kentucky	0.014
Louisiana	0.00228
Maine	0.0466
Maryland	0.0111
Massachusetts	0.00714
Michigan	0.00108
Minnesota	0.0023
Mississippi	0
Missouri	0.00442
Montana	0.0742
Nebraska	0.00593
Nevada	0.00932
New Hampshire	0.0119
New Jersey	0
New Mexico	0.000701
New York	0.0459
North Carolina	0.00896
North Dakota	0.00924
Ohio	0.000921
Oklahoma	0.00664
Oregon	0.0907
Pennsylvania	0.00203
Rhode Island	0.000096
South Carolina	0.00362
South Dakota	0.0575
Tennessee	0.026
Texas	0.000438
Utah	0.00232
Vermont	0.104
Virginia	0.000574
Washington	0.129
West Virginia	0.00518
Wisconsin	0.00668
Wyoming	0.00364

The sources used to model the American grid mixes are listed below.

Electricity production data and grid composition:

- U.S. Environmental Protection Agency. (2023). Emissions & Generation Resource Integrated Database (eGRID), 2021

SF_6 Emissions:

- U.S. Environmental Protection Agency. (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021

Global average emissions from hydropower:

- Environmental Science and Technology. (2013). Addressing biogenic greenhouse gas emissions from hydropower in LCA

Share of Reservoir in total hydro production:

- Paul Scherrer Institut. (2012). Life Cycle Inventories of Electricity Mixes and Grid

Mexican grid mix

The Mexican grid electricity process is modelled using the National Center for Energy Control (CENACE) as the primary source for 2021 data on the quantity of electricity generated by fuel type and specific electricity generation technology. Power Technology and Global Energy Monitor were used as the primary data sources to assign specific electricity generation technology for the electricity generated from biomass and hydro in Mexico.

The Mexican grid mix was determined by modelling the fraction of electricity produced by different electricity technologies used in Mexico. The Canadian technology-specific system processes were used as a proxy to represent the upstream emissions for each technology.

The sources used to model the Mexican grid mix are listed below.

General electricity production data:

- El Centro Nacional de Control de Energía (CENACE). (2021). Energía Generada por Tipo de Tecnología (Available in Spanish only)

Other electricity generating technology data (biomass and hydro):

- Power Technology. (2021). Data Insights
- Global Energy Monitor. (2021). Projects

Brazilian grid mix

The Brazilian grid electricity process was modelled using the “Operador Nacional do Sistema Elétrico” (ONS) as the primary source for 2021 data on the quantity of electricity generated by fuel type, the list of power plants that generated electricity by fuel type, and the quantity of electricity generated. Power Technology and Global Energy Monitor were the primary data sources for 2021 data to assign specific electricity generation technology for the electricity generated from biomass, coal, hydro, and natural gas in Brazil.

The Brazilian grid mix was determined by modelling the fraction of electricity produced by different electricity technologies used in Brazil. The Canadian technology-specific system processes were used as a proxy to represent the upstream emissions for each technology. Industrial waste sources in the Brazil grid mix were not accounted for due to a negligible contribution in the grid mix and a lack of data regarding technology modelling.

The sources used to model the Brazilian grid mix are listed below.

General electricity production data:

- Operador Nacional do Sistema Elétrico (ONS). (2021). Geração de Energia (Available in Portuguese only)

Other electricity generating technology data (biomass, coal, hydro, natural gas):

- Power Technology. (2021). Data Insights
- Global Energy Monitor. (2021). Projects

Argentinian grid mix

The Argentinian grid electricity process is modelled using electricity generation and emissions data reported in the “Compañía Administradora del Mercado Eléctrico Mayorista” (CAMMESA). This was the primary source for 2021 data on the quantity of electricity generated by fuel type and specific electricity generation technology. Power Technology was used as the primary data source to assign specific electricity generation technology for the electricity generated from biomass in Argentina.

The Argentinian grid mix was determined by modelling the fraction of electricity produced by different electricity technologies used in Argentina. The Canadian technology-specific system processes were used as a proxy to represent the upstream emissions for each technology. The biogas process in the Argentina grid mix was not accounted for due to a negligible contribution in the grid mix and a lack of data regarding biogas technology modelling.

The sources used to model the Argentinian grid mix are listed below.

General electricity production data:

- Compañía Administradora del Mercado Eléctrico Mayorista (CAMMESA). (2021). Informes y Estadísticas (Available in Spanish only)

Other electricity generating technology data (biomass):

- Power Technology (2021). Data Insights

3.3.3 Modelling approach for excess electricity

Excess electricity to the grid is modelled in a conservative simplified static allocation method. In this method, the boundary of the LCIF production system was expanded and the emissions associated with the yearly average CI of the provincial/state grid electricity displaced by the excess electricity are all credited to the LCIF fuel production system, up to a maximum CI. The functional unit for excess electricity processes is 1 kWh electricity produced and exported.

Canadian and American excess electricity

The processes for displaced electricity production associated with excess electricity exported to the grid have been developed for the Canadian provinces and territories, Canadian national average, and American states. The excess electricity processes were modeled using the same data and approach as for the grid mixes (please consult the previous subsections). However, because the amount of electricity sold is based on the quantity produced, the processes for excess electricity do not consider transportation and distribution to end users and therefore do not include electricity losses and SF_6 emissions in transmission and distribution.

Maximum excess electricity

The maximum displaced electricity CI was determined to prevent an overestimation of the emission reductions that are occurring from the generation of excess electricity. The goal of the method was to allocate emissions that occur at the fuel production facility to the electricity produced on site and transferred or sold to the grid or to an adjacent facility in order to not allocate these emissions to the fuel system. The goal was not to allocate emission reductions that may occur in the electricity sector to the fuel system.

The following elements were considered in the selection of this method:

1. For fuel production facilities producing electricity in excess, the most common technology used to produce electricity on-site was a cogeneration system.
2. Historically, industrial cogeneration systems are sized and operated to meet the required thermal load of the facility with the electricity output being complementary to the grid electricity supply for additional redundancy and resilience. There are a few examples of industrial cogeneration systems designed to supply electricity to the grid but these are not typical.

The other methods to model excess electricity to the grid, presented below, were considered for cogeneration systems:

1. Emission allocation based on the energy content of electricity and heat produced by the cogeneration system in the fuel production facility
2. Fuel chargeable to power, where emissions that would have been produced by a boiler to produce the thermal energy required are calculated and subtracted from the cogeneration system's total emissions, leaving only the electricity emissions

Although these other methods would have been more accurate than the simplified static allocation method, they require specific data that is unavailable or inconsistent due to the high variability occurring in cogeneration systems:

a) Electricity energy output of the cogeneration system
b) Thermal energy output of the cogeneration system
c) Fuel consumption of the cogeneration system, including fuel gas or other intermediary products that are burned in the cogeneration system, which would require the CI for the fuel gas and intermediary products to be determined
d) A reference base case for the thermal energy emission intensity would also need to be chosen for the fuel chargeable to power method

The simplified static allocation method was used to model excess electricity to the grid due to the above data gaps.

The maximum CI of 301.4 g CO_2e/kWh was set based on the simplified allocation method. It is based on the CI for a natural gas boiler with a 71% efficiency, including combustion emissions (250 g/kWh CO_2e) and upstream emissions of natural gas production based on the natural gas datasets from the Fuel LCA Model.

3.3.4 Modelling approach for electricity generation technologies

The Data library includes several technology-specific processes for electricity generation (e.g. “hydropower, reservoir”), applicable across Canada. These are listed below. The processes account for the direct emissions of electricity generation, as well as the upstream impacts of inputs to power generation, when relevant.

Available electricity technologies in the Model:

- Biomass, wood, cogeneration
- Biomass, wood, simple cycle
- Coal, bituminous
- Coal, lignite
- Coal, sub-bituminous
- Diesel
- Heavy fuel oil
- Hydro, reservoir
- Hydro, run-of-river
- Natural gas, cogeneration
- Natural gas, combined cycle
- Natural gas, converted boiler
- Natural gas, simple cycle
- Nuclear, CANDU
- Solar, concentrated solar power
- Solar, photovoltaic
- Wind, onshore

Two sets of processes are available for each technology:

- Onsite generation: they include all life cycle GHG emissions up to the point where the electricity is ready to be transferred to the grid.
- Offsite generation: they include the GHG emissions associated with onsite generation as well as those associated with transmission and distribution to the end-user. The datasets include SF_6 emissions produced by the equipment used in electricity transmission and distribution as well as electricity losses.

For onsite electricity generation processes, the functional unit is 1 kWh electricity produced onsite from the specified technology. For offsite electricity generation processes, the functional unit is 1 kWh electricity produced and delivered to the user.

Direct emissions from electricity generation and fuel consumption inputs were calculated using the CAFE3 model. Missing data are completed with literature sources and proxies.

While CAFE3 contains datasets that model the emissions for fuels used in electricity generation, these datasets were replaced, for greater coherence with the rest of the Model, with the datasets of fuels in the Model. The exception is for uranium used in nuclear power plants, for which the Ecoinvent v3.6-based LCI data was used.

Direct CO_2 emissions from the combustion of lignite and sub-bituminous coal in the CAFE3 model were found to lie in the lower range of values when compared to the emission intensities of other reputable sources and were therefore not used. Hence, values for these parameters were calculated using the HHV and CO_2 emission factors from the NIR (2018).

Emissions from hydroelectric reservoirs are accounted for based on net CO_2 and CH_4 emissions from lands flooded to produce reservoirs over 100 years (Levasseur et al., 2021). While these values are based on Quebec reservoirs, they are used as proxies for reservoir emissions for all reservoirs in Canada.

The SF_6 emissions produced by the equipment used in electricity transmission and distribution as well as electricity losses are based on 2018 data from the NIR (Table A13-1).

The sources used to model the electricity generation technologies are listed below.

Electricity production data and grid composition:

- Government of Canada. (2023). National Inventory Report 1990-2021: Greenhouse Gas Sources and Sinks in Canada.

Direct emissions from electricity generation and fuel consumption:

- Environment and Climate Change Canada. Canadian Analytical Framework for the Environmental Evaluation of Electricity (CAFE3).

Hydro-reservoir biogenic emissions factors:

- Levasseur, A., S. Mercier-Blais, Y. T. Prairie, A. Tremblay, and C. Turpin. 2021. Improving the Accuracy of Electricity Carbon Footprint: Estimation of Hydroelectric Reservoir Greenhouse Gas Emissions. Renewable and Sustainable Energy Reviews 136 (February): 110433.

3.4 Other energy sources

The Data library has three additional energy source processes representing purchased steam, non-biogenic waste combustion, and fuel gas combustion.

3.4.1 Purchased steam

The purchased steam process was developed with a functional unit of 1 MJ of steam generated from a natural gas boiler. The scope of the process includes the direct emissions from the combustion of natural gas in addition to the upstream emissions related to the production and distribution of the natural gas. Direct emissions of the natural gas boiler were set to 223 g CO_2e per kWh of steam generated, assuming a boiler efficiency of 80%. The natural gas processes in the Model were used to determine the amount of natural gas needed to produce 1 MJ of steam. Natural gas modelling is described in **Chapter 3.6**.

3.4.2 Non-biogenic waste combustion

The “Non-biogenic waste combustion” process was developed to model the combustion of non-biogenic waste materials used as a fuel. The process was developed with a functional unit of 1 kg of non-biogenic waste combusted. The scope of the process only includes the combustion emissions of non-biogenic waste used as fuel input. In accordance with the cut-off allocation rule (see **Chapter 2.6**), the production of the non-biogenic waste is excluded from the dataset. In addition, transportation to the end-user is excluded because it is expected that in most cases the waste is produced onsite or nearby.

The combustion is modelled using the emission factor and HHV (36.2 MJ/kg) for petcoke combustion as a proxy. Petcoke combustion emission factors for CO_2, CH_4 and N_2O (when used as an energy source) in the refinery sector are sourced from the NIR (Government of Canada, 2018).

3.4.3 Fuel gas combustion

Fuel gas is a gas commonly composed primarily of CH_4 that is used as a fuel input. Fuel gas also contains other gases such as water or other hydrocarbons. The Model includes fuel gas as an energy input. The process is modelled using natural gas combustion as a proxy. Natural gas combustion modelling is described in **Chapter 3.6.2**.

3.5 Feedstocks

The Data Library contains six main categories of feedstock that can be used in LCIF pathways: animal fats, crops (field peas, grains, and sugar cane), residues, waste, wood fibre, and yellow grease.

The following sections present the modelling approach and assumptions used to model the CI associated with the production and/or the collection of the six feedstock categories found in the “Feedstocks” folder of the Data Library.

It should be noted that are other processes that can be considered as feedstock. For example, natural gas can be used as feedstock for hydrogen production; natural gas processes can be found in the “Fossil fuels” folder. Details for fossil fuel extraction and production are available in **Chapter 3.6**. In addition, the Model includes some configurable processes that can be used to model feedstock processes that are not included the Data Library. These processes are documented in **Chapter 4.2**.

3.5.1 Animal fats production

Modelling approach for the production of animal fats from animal by-products

The boundary of the production of animal fats begins with the transport of the animal by-products from the slaughterhouse to the rendering plant and ends with the production of animal fat. The upstream GHG emissions related to animal by-product are not included in the modeling since it is considered a waste. A trucking distance of 100 km is assumed. Animal by-products from the slaughterhouse are processed in a rendering plant to produce animal fat, with meat and bone meal as co-products. Natural gas and heavy fuel oil are used for the thermal energy requirements of the rendering process, and the values used for the modeling are based on average values from table 1 of Chen 2017. The cooking vapours are a waste stream and are excluded from calculations. An overview of the processing steps involved in the production of animal fat is presented in **Figure 5**.

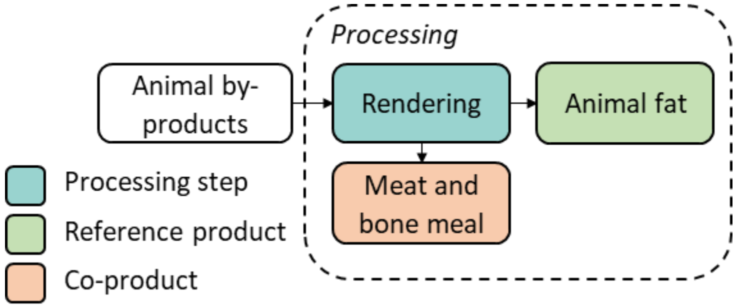

Figure 5: Processing overview for rendering of animal by-products into animal fat

Geographical scope for rendering animal by-products into animal fat

The Model includes processes defined at the provincial and national levels for animal fat production in Canada. All Canadian processes were based on U.S. data on rendering of animal by-product. Processes only differ in the provincial electricity grid mix used in the rendering process. This assumes that the production process does not differ across Canada, and only the emissions related to electricity differ.

Allocation approach for rendering animal by-products into animal fat

The allocation of burdens to the meat and bone meal and animal fat at the rendering plant is performed according to the dry mass content of the products.

Data sources for rendering animal by-products into animal fat

The main data source used to model animal fat rendering is listed below. Beef tallow was used as a proxy for animal fats.

- Chen, R., Qui, Z., Canter, C., Cai, H., Han, J., & Wang, M. (2017, October 9). Updates on the energy consumption of the beef tallow rendering process and the ration of synthetic fertilizer nitrogen supplementing removed crop residue nitrogen in GREET.

3.5.2 Cultivation of agricultural crops

The Data Library includes the following agricultural crops:

- Corn
- Durum wheat
- Non-durum wheat
- Sorghum
- Barley
- Field peas
- Sugar cane

The following sections present the modelling approach for the agricultural crops. The crops are grouped by the main data sources used for modelling. The first section presents the modelling for corn, wheat (durum and non-durum), barley, and field peas, the second section presents the modelling for sorghum, and the third section presents the modelling for Brazilian sugar cane. The modelling approach is similar for the crops presented in first and second sections, while the modeling approach for sugar cane is different. For each of these feedstocks, the functional unit is 1 kg of dry mass crop at the farm gate.

Modelling approach for corn, wheat, barley, and field peas cultivation

The boundaries of each crop dataset include all field activities related to crop production (from soil preparation to harvest and storage). It excludes the subsequent transportation, distribution, processing and use phase of the harvested crops. The LCI for each crop was modelled based on the 2022 LCA studies for major crops from the CRSC.

Each crop was modelled using eight production processes: tillage, seeding, irrigation[12], fertilizer and 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 as well as agricultural inputs such as fertilizers, pesticides and seeds were considered for all processes. **Figure 6** illustrates the process flow, which includes the inputs considered as well as the functional unit.

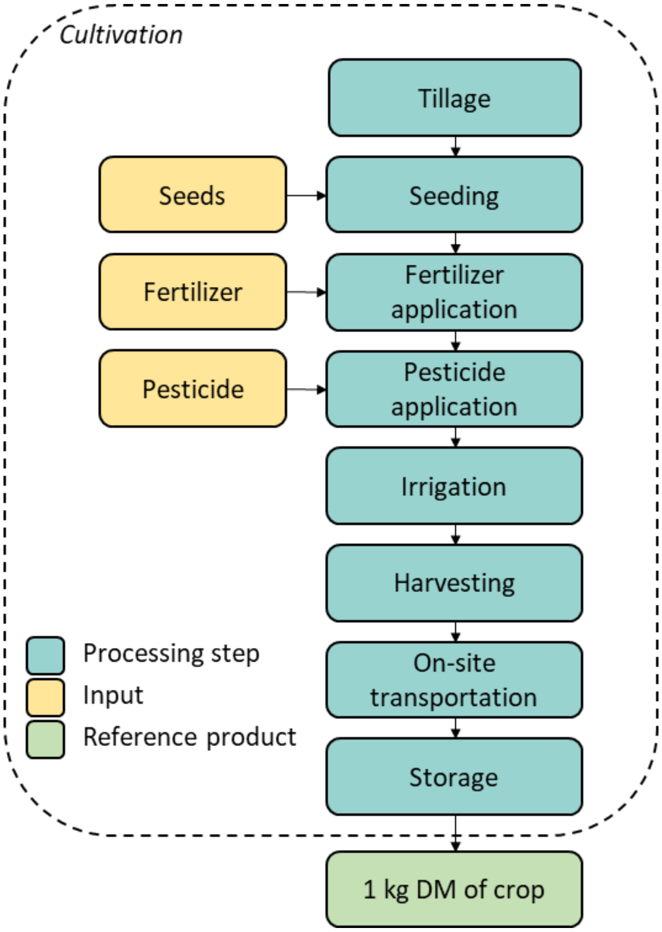

Figure 6: Cultivation overview for agricultural feedstocks, which represents the feedstock production life cycle stage.

Tillage techniques (i.e. conventional tillage or intensive tillage, reduced tillage and direct seeding or no-tillage) were considered for the calculation of energy use in the form of diesel fuel consumption, direct N_2O emissions and soil carbon changes.

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[12] Only energy use for irrigation was considered; irrigation water was not included in the model because it is outside the scope of the Model.

The scope of the Model also includes direct and indirect N_2O emissions from nitrogen inputs (nitrogen-fertilizers, crop residues and mineralized nitrogen from soil) as well as CO_2 sequestration and emissions from land management practices. N_2O emissions for Canadian grown crops were calculated using Tier 2 emission factors from the CRSC reports which take into account tillage type, irrigation practices, and topography.

In accordance with the approach in the NIR (2023), carbon emissions associated with SOC changes in Canada are included for the two following land management practices:

- Changes in crop productivity and crop residue carbon inputs
- Change in tillage practices (i.e. no till, reduced till and conventional till)

The CRSC data on SOC that was included in the Model covered changes in soil carbon up to the year 2020.

As justified in the CRSC report, the following elements were either excluded from the scope of the LCI due to lack of data or because the contribution of some of these inputs to the CI was negligible:

- on-farm production of renewable energy, such as solar, wind, and biomass combustion
- on-farm ancillary operations, such as work area lighting and heating
- manufacture, maintenance and decommissioning of capital equipment (e.g. machinery, trucks, infrastructure)
- transport of pesticides and fertilizers between the manufacturing plant and the farm.
- waste or co-products, such as:
    - disposal of process wastes
    - straw and stover co-products
    - emissions related to manure application

In addition, carbon emissions from changes in the proportion of annual and perennial crops were excluded because of methodological concerns raised related the application of Canadian Soil SOC values to U.S. crops[13].

Regarding the exclusion of organic fertilizers such as manure, the Model uses the default approach from the *Livestock Environmental Assessment and Performance guidelines*[14] which is to consider manure as a residue co-product of livestock systems. Emissions and resource use related to manure storage and application are therefore allocated to the livestock farm. In this approach the N_2O emissions associated with the application of the manure are also attributed to the livestock production.

Geographical scope for Canadian grown agricultural crop cultivation

There is one system process available for each crop, with each crop having a unique CI, and each process can be used regardless of geographical location. Agricultural feedstock LCI data was collected and compiled for each province, with the exception of Newfoundland and Labrador. A weighted average of

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[13] This approach will be reassessed in 2026.

[14] FAO. 2016. Livestock Environmental Assessment and Performance (LEAP) Partnership. Food and Agriculture Organization of the United Nations (fao.org)

the provincial datasets was then calculated for each crop using 2018/2020 average production data from Statistics Canada. **Table 4** indicates which regions were included in the CI calculations for each crop.

Table 4: Geographical scope of barley, corn, wheat (durum and non-durum), and field peas included in the Model

Crop	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
Barley	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Corn	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Wheat (Durum)	Yes	No	Yes	No	No	No	No	No	No	Yes
Wheat (non Durum)	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Field Peas	Yes	Yes	Yes	Yes	No	No	No	Yes	No	Yes

The provincial data, was also calculated using weighted averages of regional data at the reconciliation unit (RU) level when available. RUs are the geographic entities formed by the intersection of terrestrial ecozones of Canada with the provincial and territorial boundaries. They are used to reconcile data from multiple agencies of the Government of Canada. **Figure 7** shows the RU breakdown in Canada.

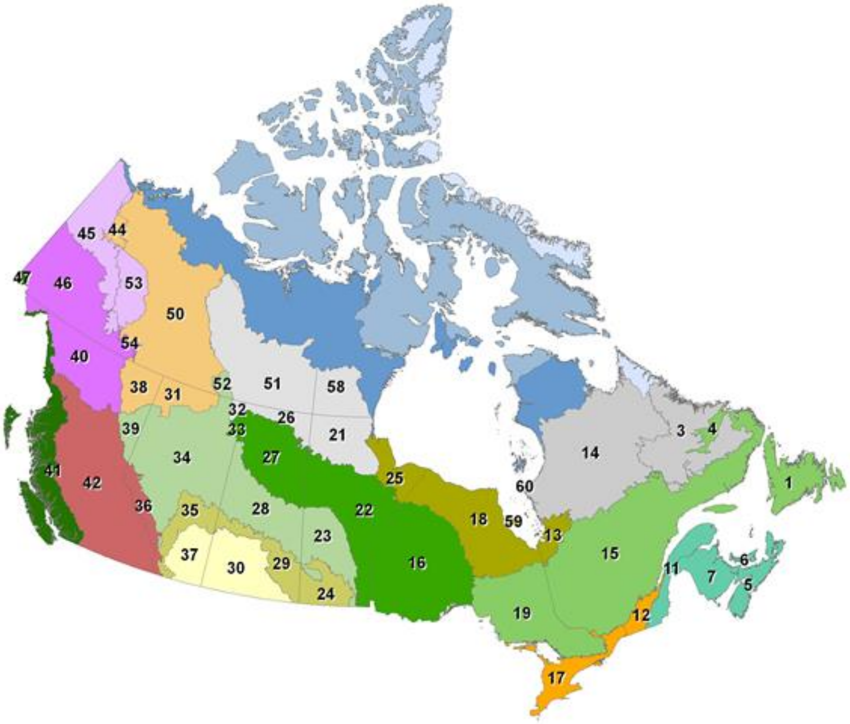

Figure 7: RUs in Canada[15]

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[15] Natural Resources Canada. NFCMARS - spatial framework.

Allocation for Canadian grown agricultural crop cultivation

Crop cultivation results in agricultural residues that are left on the field. The Model considers these residues as a waste (i.e. not co-product) from the crop cultivation and the "cut-off" allocation approach is applied (see **Chapter 3.5.3**). No other allocation procedure was applied to the LCI dataset of agricultural crops.

Data sources for Canadian grown agricultural crop cultivation

The Carbon Footprint Methodology report from the CRSC carbon footprint studies, along with the crop-specific CRSC reports for wheat, barley and field peas were the main sources of data for compiling these LCI. Most of the LCI for corn were built using the same data sources from the CRSC reports and the modelling approach remained the same ((S&T)^2 Consultants Inc. 2022f). The CRSC studies represent the current best available source of Canadian field crop LCI data.

The CRSC reports detail carbon footprints of wheat, barley, and field peas in Canada using a variety of data sources: national statistics, provincial field crop budgets and agricultural surveys, data from provincial agricultural associations and literature data. The reports contain detailed information regarding fertilizer, pesticide and seeding rates as well as energy consumption values for crop production. Although data sources sometimes vary between crops depending on data availability, the modelling approach is consistent for all crops. The methodology and data sources are also consistent with those used in the NIR with respect to N_2O emissions from managed soils and land management practices.

The CIs related to the production of fertilizer and pesticide for the field activities were modelled as are explained in more details in **Chapter 3.1.2**. The main data sources to model agricultural crop feedstocks are listed below.

Data sources for agriculture crop cultivation

- (S&T)^2 Consultants Inc. (2010). Life cycle analysis of canola biodiesel. Winnipeg, MC: Canola Council of Canada.
- (S&T)^2 Consultants Inc. (2022a). Updated Carbon Footprint for Canadian Barley. Ottawa, ON: Canadian Roundtable on Sustainable Crops.
- (S&T)^2 Consultants Inc. (2022b). Updated Carbon Footprint for Canadian Canola. Ottawa, ON: Canadian Roundtable on Sustainable Crops.
- (S&T)^2 Consultants Inc. (2022c). Updated Carbon Footprint for Canadian Dried Peas. Ottawa, ON: Canadian Roundtable on Sustainable Crops.
- (S&T)^2 Consultants Inc. (2022d). Updated Carbon Footprint for Canadian Durum Wheat. Ottawa, ON: Canadian Roundtable on Sustainable Crops.
- (S&T)^2 Consultants Inc. (2022e). Updated Carbon Footprint for Canadian Wheat. Ottawa, ON: Canadian Roundtable on Sustainable Crops.
- (S&T)^2 Consultants Inc. (2022f). Updated Carbon Footprints for Major Canadian Grains Methodology Report. Ottawa, ON: Canadian Roundtable on Sustainable Crops.
- Agriculture (2018a). Crop Planning Guide. Regina, SK: Government of Saskatchewan.
- Agriculture (2018b). Specialty Crop Report. Regina, SK: Government of Saskatchewan.

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- Chen, R., Qin, Z., Han, J., Wang, M., Taheripour, F., Tyner, W., Duffield, J. (2018). Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts. Bioresource techology, 251, 249-258.
- Farm & Food Care Ontario (2014). Ontario Pesticide Survey (2013/2014).
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- OMAFRA (2022). Ontario Ministry of Agriculture, Food and Rural Affairs (2022). Agronomy Guide for Field Crops: Publication 811.
- OMAFRA (2024). Ontario Ministry of Agriculture, Food and Rural Affairs (2024). Publication 60: Field Crop Budgets 2024.
- Shonnard, D., Williams, L., & Kalnes, T. (2010). Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. Environ. Prog. Sustainable Energy, 29, 382-392.
- Statistics Canada. Table 32-10-0002-01 Estimated areas, yield and production of principal field crops by Small Area Data Regions, in metric and imperial units
- Statistics Canada. Table 32-10-0038-01 Fertilizer shipments to Canadian agriculture and export markets, by product type and fertilizer year, cumulative data (x 1,000)
- Stratus Ag Research (2017). Fertilizer Use Survey – Ontario Report (2016 Crop Year).
- Stratus Ag Research (2018). Fertilizer Use Survey (2017 Crop Year).
- Stratus Ag Research (2020). Fertilizer Use Survey (2019 Crop Year).
- Stratus Ag Research (2021). Fertilizer Use Survey (2020 Crop Year) Ontario.
- USDA (2010). United States Department of Agriculture (2010). Agricultural Resource Management Survey (ARMS), conducted by the National Agricultural Statistics Service and the Economic Research Service. USDA Corn and Other Feed Grains.
- USDA 2012. United States Department of Agriculture (2012). Agricultural Resource Management Survey (ARMS), conducted by the National Agricultural Statistics Service and the Economic Research Service. USDA Soybean and Oil Crops.

Modelling approach for sorghum

The dataset for sorghum was generated based on a report developed for ECCC by consultancy firm, Quantis. As with the modelling of other crops, the boundaries of the sorghum dataset considered of all field activities related to crop production (from soil preparation to harvest and storage) and excluded the subsequent transportation, distribution, processing and use phase of the harvested grains and oilseeds. The LCI was modelled based on data generated by the geoFootprint tool. The geoFootprint tool was developed by Quantis and models the footprints of agricultural commodities around the world by accounting for local environmental conditions (soil and climate) in conjunction with best estimates of regional farm management practices. The tool relies entirely on publicly available data which have been consolidated and harmonized. All modelling steps, assumptions and data sources are described in the geoFootprint Technical Documentation, which is publicly available on the geoFootprint website[16].

Sorghum was modelled using the same eight production processes as other crops included in the Data Library: tillage, seeding, irrigation[17], fertilizer and 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 as well as agricultural inputs such as fertilizers, pesticides and seeds were considered for all processes.

Similarly, tillage techniques (i.e. conventional tillage or intensive tillage, reduced tillage and direct seeding or no-tillage) were considered for the calculation of energy use in the form of diesel fuel consumption, direct N_2O emissions and soil carbon changes.

N_2O emissions for international crops are calculated using a modified IPCC Tier 1 equation. Data was collected for the geoFootprint N_2O modelling approach using the Bouwman model[18] as implemented by the Cool Farm Tool[19].

Carbon emissions associated with SOC changes from the two following land management practices are included:

- Changes in area of summerfallow
- Change in tillage practices (i.e. no till, reduced till and conventional till)

Canadian national harvest-area weighted average values for SOC changes were applied to crops grown internationally.

The modelling scope for the development of the LCI of sorghum followed the same scope as other crops and excludes the following:

- carbon emissions associated with SOC changes from changes in the proportion of annual and perennial crops
- on-farm production of renewable energy, such as solar, wind, and biomass combustion
- on-farm ancillary operations, such as work area lighting and heating
- manufacture, maintenance and decommissioning of capital equipment (e.g. machinery, trucks, infrastructure)
- transport of pesticides and fertilizers between the manufacturing plant and the farm
- waste or co-products, such as:
    - disposal of process wastes

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[16] Reinhard J., Bengoa X. & Liernur A. (2021): geoFootprint, Technical Documentation. Version 1, February 2021. Quantis, Lausanne, Switzerland.

[17] Only energy use for irrigation was considered; irrigation water was not included in the model because it is outside the scope of the Fuel LCA Model.

[18] Bouwman AF, Boumans LJM, Batjes NH (2002) Modeling global annual N2O and NO emissions from fertilized fields. Glob Biogeochem Cycles 16:28–29.

[19] Kayatz B, van Tonder C, Hillier J, et al (2020) Cool Farm Tool Technical Documentation. Cool Farm Alliance, UK.

    - straw and stover co-products
    - emissions related to manure application

Organic fertilizers such as manure were excluded from the scope.

Geographical scope for sorghum

LCI data for sorghum was generated by the geoFootprint tool based on data from the U.S. The energy and material inputs (e.g. fertilizers, pesticide, diesel, etc.) were modelled using the datasets from the Model. A weighted average of regional data from Kansas, Missouri, Nebraska, and Texas was used to create a single process in the Data library.

The geoFootprint geographical unit of analysis (the most fundamental level at which data is held and processed) is at the grid cell level. GeoFootprint operates on a grid cell resolution 5 x 5 arc-minutes (i.e., 10 x 10 km at the equator). GeoFootprint aggregates grid cells to the State level. For each state, a specific number of grid cells is considered in the aggregation. Grid cells included in the aggregation must have a scaled production volume higher than a given threshold. For sorghum, the threshold, is 20.00 metric tons per grid cell.

Allocation for sorghum

Agricultural residues that are left on the field are considered a waste (i.e. not a co-product) from the crop production and the “cut-off” allocation approach is applied (see **Chapter 3.5.3**). No other allocation procedure was applied to the LCI dataset of agricultural crops.

Data sources for sorghum

The geoFootprint tool was the main source of data for compiling the internationally grown crop inventories.

The tool uses two clusters of raw data as its foundation. The first cluster of data consists of consolidated LCI datasets representing country-level cultivation practices. These data are derived from the World Food LCA Database[20] (WFLDB) and from the Ecoinvent database[21] (Weidema et al. 2013). These datasets are all rasterized and harmonized with regards to their resolution and projection system and then overlaid to create grid cell specific LCIs. Where more granular spatial data is available for a given parameter, it overwrites the value extracted from the default inventory at country-level. The second, a repository of publicly available geospatial data for key parameters reflecting certain farm management practices (e.g. harvested areas, yields, fertilizer application rates, manure application rates) and environmental conditions (e.g. soil pH, soil clay content, SOC stock, temperature, rainfall).

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[20] Nemecek T., Bengoa X., Lansche J., Roesch A., Faist-Emmenegger M., Rossi V. & Humbert S. (2019) Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 3.5, December 2019. World Food LCA Database (WFLDB). Quantis and Agroscope, Lausanne and Zurich, Switzerland.

[21] Weidema B.P., Bauer C., Hischier R., Mutel C., Nemecek T., Reinhard J., Vadenbo C.O., Wernet G. (2013). Overview and methodology. Data quality guideline for the Ecoinvent database version 3. Ecoinvent Report 1(v3). St. Gallen: The Ecoinvent Centre.

Some data points of key relevance (i.e. harvested area, production volume, yield) are retrieved from the EarthStat[22] consortium (Monfreda, 2008), which modelled the expected cultivation properties for 172 crops at a resolution of 10x10 km worldwide, for the year 2000. In geoFootprint, these data are therefore scaled to provide the best possible representation of these properties in 2016. A full list of parameters and data sources are found in **Table 5**.

Table 5: Parameters and data sources in geoFootprint

Parameter	Data source	Native resolution	Scaling method	Aggregation method
Harvested crop area	EarthStat (Monfreda, 2008)	10 x 10 km	Based on FAOSTAT[23] data evolution from (1999-2001) to (2015-2017)	Sum
Yield	EarthStat (Monfreda, 2008)	10 x 10 km	Based on FAOSTAT[23] data evolution from (1999-2001) to (2015-2017)	Production Volume Weighted Average
Production volume	EarthStat (Monfreda, 2008)	10 x 10 km	Based on FAOSTAT[23] data evolution from (1999-2001) to (2015-2017)	Sum
Irrigation water withdrawal	WFN[24] (Mekonnen & Hoekstra, 2011)	10 x 10 km	n/a	Production Volume Weighted Average
Surface irrigation	WFLDB (Nemecek et al. 2019)	Country	n/a	Constant at country-level
Sprinkler irrigation	WFLDB (Nemecek et al. 2019)	Country	n/a	Constant at country-level
Drip irrigation	WFLDB (Nemecek et al. 2019)	Country	n/a	Constant at country-level
Nitrogen fertilizer	EarthStat (Monfreda, 2008)	10x10 km	n/a	Production Volume Weighted Average
Phosphorus fertilizer	EarthStat	10x10 km	n/a	Production Volume Weighted Average

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[22] Monfreda C, Ramankutty N, Foley JA (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Glob Biogeochem Cycles 22.

[23] FAO (2020). FAOSTAT Database.

[24] Mekonnen MM, Hoekstra AY (2011). The green, blue and grey water footprint of crops and derived crop products. Hydrol Earth Syst Sci Discuss 8:763–809.

Parameter	**Data source**	**Native resolution**	**Scaling method**	**Aggregation method**
	(Monfreda, 2008)			
Potassium fertilizer	EarthStat[25] (Mueller et al., 2012)	10x10 km	n/a	Production Volume Weighted Average
Fuel consumption	WFLDB (Nemecek et al. 2019) Ecoinvent (Weidema et al., 2013)	Country	n/a	Constant at country-level
Crop protection	WFLDB (Nemecek et al. 2019) Ecoinvent (Weidema et al., 2013)	Country	n/a	Constant at country-level
SOC stock	ISRIC Soil Grids[26] (Hengl et al., 2014)	10x10 km	n/a	Simple Average
Clay content	ISRIC Soil Grids[26] (Hengl et al., 2014)	10x10 km	n/a	Simple Average
Silt content	ISRIC Soil Grids[2626] (Hengl et al., 2014)	10x10 km	n/a	Simple Average
Sand content	ISRIC Soil Grids[26] (Hengl et al., 2014)	10x10 km	n/a	Simple Average
Precipitation	GAEZ[27] (FAO, IIASA, 2009)	10x10 km	n/a	Simple Average
Temperature	GAEZ[27]	10x10 km	n/a	Simple Average

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[25] Mueller ND, Gerber JS, Johnston M, et al (2012) Closing yield gaps through nutrient and water management. Nature 490:254–257.

[26] Hengl T, de Jesus JM, MacMillan RA, et al (2014) SoilGrids1km — Global Soil Information Based on Automated Mapping. PLoS ONE 9:e105992.

[27] FAO/IIASA/ISRIC/ISS-CAS/JRC (2009) Harmonized World Soil Database (version 1.1). FAO & IIASA, Rome, Italy & Laxemburg, Austria.

Parameter	Data source	Native resolution	Scaling method	Aggregation method
	(FAO, IIASA, 2009)			

Modelling approach for sugar cane

Data used for the modeling of the sugar cane process comes from the RenovaCalc tool of the RenovaBio certification program implemented by the Brazilian government though 2019 and 2020. As part of the program, producers had to submit CI data for the ethanol derived from sugar cane that they produced, including for the cultivation of sugar cane. RenovaBio is also a source of input data for other publications dealing with Brazilian sugarcane cultivation listed in the *Data sources for sugar cane* section.

The modelling considers the following material inputs, energy inputs and outputs emissions for the CI calculation:

- Synthetic fertilizers
- Pesticide application
- Direct on-site energy requirements
    - Fuel consumption (biodiesel, gasoline, diesel, hydrous ethanol)
    - Electricity (modeled with the Brazilian electricity grid mix in the Model)
- Direct and indirect N_2O emissions (both volatilization and leached)
- Emissions from burning practices
- Upstream emissions associated with soil amendments
- Direct emissions associated limestone and urea

For data on the application rate for pesticides, assumptions from GREET 2023 Feedstock CI Calculator were used. The IPCC 2019 disaggregated N_2O emission factors for wet climate were used for the direct and indirect volatilized emission factor (EF1 and EF4), while the aggregated values from IPCC 2019 were used for the indirect leached emission factor (EF5) and the fractions leached and volatilized from synthetic and organic fertilizers (IPCC 2019, Tables 11.1 and 11.3).

Geographical scope for sugar cane

The process in the Model corresponds to the cultivation of sugar cane in Brazil. The process takes aggregated data from a total of 67 ethanol production mills in Brazil that have published their performance data for public review, including data on the cultivation of sugar cane.

Allocation for sugar cane

No allocation is required for the cultivation process of sugar cane.

Data sources for sugar cane

- RenovaBio (2021). RenovaCalc Life Cycle Assessment tool, Version 7, published on July 4, 2021 and made available on the Brazilian government's website (available in Portuguese only).
- Don O'Connor, (S&T)^2 Consultants Inc. IEA Bioenergy: Task 39. Life Cycle Inventory Data for Brazilian Sugarcane Production. February 2022.
- Xinyu Liu, Hoyoung Kwon, Michael Wang, and Don O'Connor (2023). Life Cycle Greenhouse Gas Emissions of Brazilian Sugar Cane Ethanol Evaluated with the GREET Model Using Data

Submitted to RenovaBio. Environmental Science & Technology 2023 57 (32), 11814-11822 DOI: 10.1021/acs.est.2c08488

- Wang, Michael, Elgowainy, Amgad, Lu, Zifeng, Baek, Kwang H., Bafana, Adarsh, Benavides, Pahola T., Burnham, Andrew, Cai, Hao, Cappello, Vincenzo, Chen, Peter, Gan, Yu, Gracida-Alvarez, Ulises R., Hawkins, Troy R., Iyer, Rakesh K., Kelly, Jarod C., Kim, Taemin, Kumar, Shishir, Kwon, Hoyoung, Lee, Kyuha, Lee, Uisung, Liu, Xinyu, Masum, Farhad, Ng, Clarence, Ou, Longwen, Reddi, Krishna, Siddique, Nazib, Sun, Pingping, Vyawahare, Pradeep, Xu, Hui, and Zaimes, George. Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2023 .Net). Computer Software. USDOE Office of Energy Efficiency and Renewable Energy (EERE). Jan. 2023. GREET 2023 Feedstock CI Calculator. Developed by Argonne National Laboratories
- IPCC (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; 2019., Chapter 11: N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application.

3.5.3 Agricultural crop residues cultivation

Modelling approach for agricultural crop residues cultivation

The Model includes a system process that models the collection of agricultural crop residues. These residues comprise the above-ground parts of the corn and wheat plants that are left on the fields after harvest. The crop residue feedstock process included in the Model is an average of corn stover, non-durum wheat straw, and durum wheat straw. Consequently, the dataset is applicable for residues from corn and wheat production only.

Given that most crop residues are currently left on agricultural fields, agricultural residues are treated as waste products in the Model. As such, no upstream impacts from cultivation are allocated to the residues. However, the modelling of crop residues includes the use of diesel to account for the collection of these residues, as well as an N-fertilizer input to account for the removal of these crop residues. Furthermore, because the residues contain nitrogen which is removed from the field, the field will require an additional nitrogen (N) input from N-fertilizers the following year. The quantity of nitrogen removed from the fields in residues is calculated using data from Thiagarajan et al. (2018) on the nitrogen content of corn stover and wheat straw.

The energy use input for the collection of residues is modelled based on fuel consumption for farm machinery compiled by Withman et al. (2011). The fuel consumption is estimated by hectare for a multiple passes collection process with conventional farm machinery and considers the quantity of residues by hectare. Residues quantities by hectare estimated using a relative yield of crop residues per kg of crops from Janzen et al. (2003). The collection process produces a functional unit of 1 kg dry mass of crop residues at the farm gate (before transportation to the LCIF production facility).

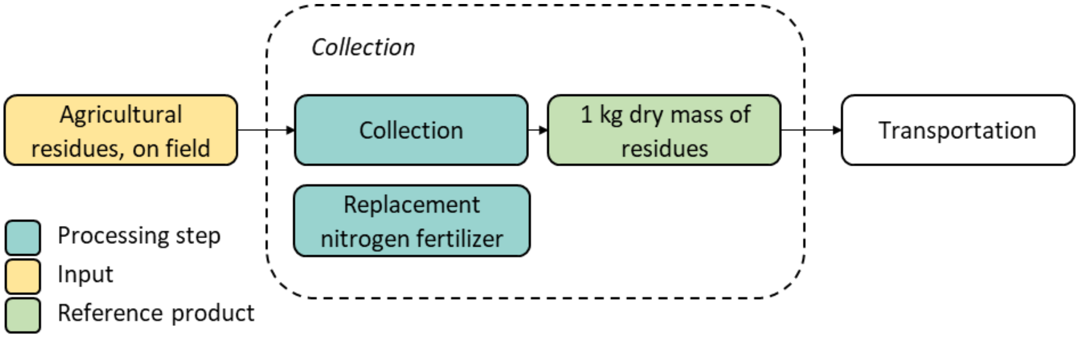

Figure 8: Crop residue collection process overview

Geographical scope for agricultural crop residues collection

The process was modelled using Canadian data, but can be used regardless of geographical location.

Allocation for agricultural crop residues collection

Agricultural residues are considered as a waste during crop cultivation and the “cut-off” allocation approach is applied. System expansion is applied to account for the production of replacement nitrogen fertilizer.

Data Sources for agricultural crop residues collection

The nitrogen content and yield of crop residues was modelled based on Thiagarajan et al. (2018). Diesel consumption for harvesting per kg of residues were estimated based off yield data from the CRSC reports and Janzen et al. (2003) and average fuel consumption by hectare from Withman et al. (2011). The data is summarized by data type below.

Nitrogen content of crop residues:

- Thiagarajan, A., Fan, J., McConkey, B.G., Janzen, H., Campbell, C.A. (2018). *Dry matter partitioning and residue N content for 11 major field crops in Canada adjusted for rooting depth and yield*. Can. J. Soil Sci. 98: 574-579

Diesel use for collection of crop residues:

Yield data from the CRSC reports:

- (S&T)2 Consultants. (2017). *Carbon Footprint for Canadian Grain Corn.* Winnipeg, MB: Canadian Roundtable on Sustainable Crops
- (S&T)2 Consultants. (2017). *Carbon Footprint For Canadian Wheat.* Winnipeg, MB: Canadian Roundtable on Sustainable Crops

Relative yield of crop residues:

- Janzen, H. & Beauchemin, Karen & Bruinsma, Y. & Campbell, C. & Desjardins, Raymond & Ellert, B.H. & Smith, E.G.. (2003). The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. Nutrient Cycling in Agroecosystems. 67. 85-102. 10.1023/A:1025195826663

Diesel consumption per hectare:

- Whitman, T., Yanni, S.F. and Whalen, J.K. (2011). *Life cycle assessment of corn stover production for cellulosic ethanol in Quebec.* Can. J. Soil Sci. 91: 997-1012

3.5.4 Other waste materials

Modelling approach for other waste materials

Wastes from various agricultural, commercial and industrial activities can be used as feedstock for many LCIFs, including ethanol, biodiesel, biogas/RNG and hydrogen.

The Model includes three generic processes for waste (two for biogenic waste and one for non-biogenic waste) which can be used to model a number of waste materials other than the feedstocks already included in the Data library. In accordance with the “cut-off” allocation approach, there is no burden associated with these processes, but they are differentiated between waste with biogenic and non-biogenic carbon content. This distinction is important for the combustion life cycle stage of the fuel (see **Chapter 3.7.1**).

However, when a waste material is used as a feedstock for fuel production, the transportation and processing of these waste feedstocks should be included in the fuel life cycle using the relevant processes from the Data library of the Model.

The use of some waste feedstocks for fuel production can prevent emissions that would have occurred if the waste materials were not used as feedstocks. For example, livestock manure used to produce biogas or RNG can prevent CH_4 emissions from manure management practices. Although the processes for waste feedstocks in the Model do not include any predefined quantities of avoided emissions, the Model allows users to enter the quantity of avoided emissions in the waste processes. The methodology for calculating these avoided emissions may vary according to the program for which the Model is used.

3.5.5 Production of wood fibre feedstock in Canada

Modelling approach for wood fibres production

The Canadian forest sector produces several types of wood fibres which can be used as feedstock for LCIF production; the 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. The Model includes the following wood fibre feedstocks:

- Coproducts, from sawmill
- Wood chips, from unmerchantable logs
- Wood pellets, from sawmill coproducts
- Wood pellets, from unmerchantable logs

Figure 9 presents the process flow and interaction between the different wood fibre feedstocks included in the Fuel LCA Model. The feedstock production life cycle stage includes harvesting and processing of the aforementioned feedstock sources, and concludes with the production of the main wood fibre feedstocks.

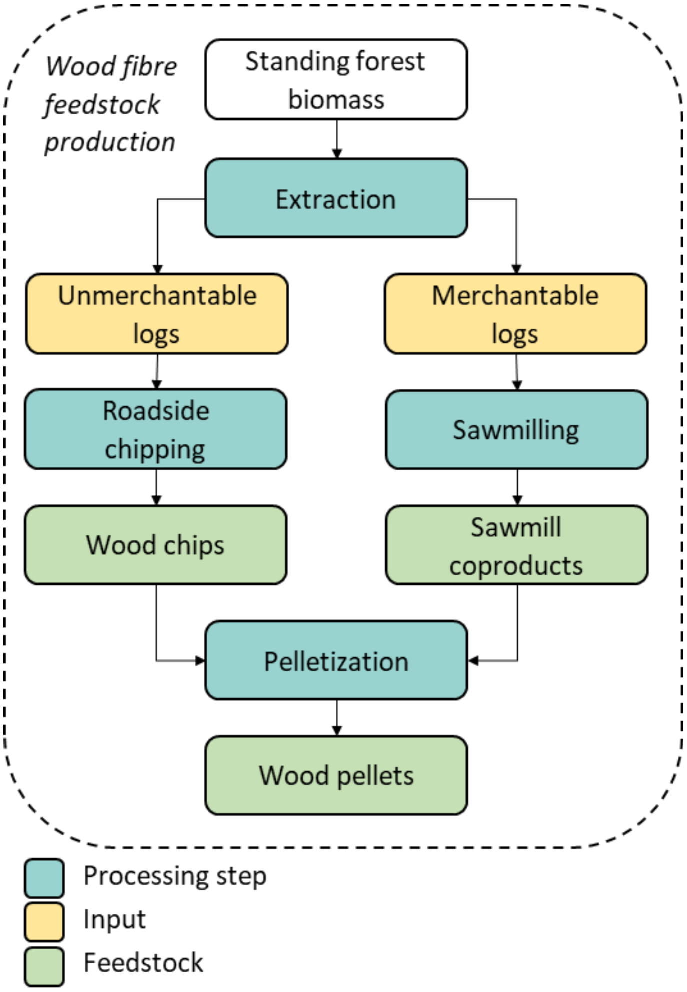

Figure 9: Harvesting and feedstock production process overview for wood fibre feedstocks

Merchantable logs and unmerchantable logs from standing forest biomass are modelled as sources of wood fibre in the preparation of wood chips or sawmill co-products as feedstocks. These feedstocks can subsequently be compressed into pellets, also available as feedstock.

The LCI for merchantable logs includes fossil fuel use (diesel, propane and gasoline) related to collection and harvesting operations and excludes any other material or chemical inputs (related to wood production, for example) which were not accounted for in the LCA data sources. For example, the best publicly available LCI data for Canadian forest harvesting operations for merchantable logs is from the Athena Sustainable Materials Institute, which was used as a data source for the LCI of merchantable logs. Seeding and planting activities are excluded from the scope of the LCI because emission factors for these inputs were not available and they did not account for GHG emissions associated with these activities. Similarly, unmerchantable logs are modelled based on the amount diesel consumed related to forestry operations. The modelling approach for unmerchantable logs only considers the collection activities, which is consistent with the approach to crop residues. Logs are transported at the roadside and converted into wood chips.

Once transported to the sawmill, merchantable logs are converted into lumber, a process which generates sawdust and wood chips, as well as other co-products (bark, shavings, trim ends and chipper fines). The woodchips and sawmill co-products can be converted in wood pellets. A trucking distance of 100 km is assumed for log transport to the sawmill from the forest. The modelling therefore allocates the energy consumption (i.e. electricity and fossil fuel use) of sawmill operations based on the mass content of the different sawmill co-products. Drying energy used in the sawmill is attributed to the sawlogs.

The chipping of unmerchantable logs at the forest roadside can be done using a wide range of technologies with varying capabilities and fuel consumption. Roadside chipping of wood biomass was based on an average diesel consumption value per amount of wood chipped based on the literature.

The pelletization process converts wood chips (and other sawmill co-products) into wood pellets. It is modelled based on the amount of energy and materials consumed at the pelletization plant; this includes energy use for hammer mill, drying, compression, cooling and sieving steps of the pelletization process as well as diesel for on site machinery and vegetable oil for lubrication. It is assumed that thermal energy for drying is partially derived from biomass. A trucking distance of 100 km is assumed from the sawmill to the pellet plant.

Excluded processes and their justification are described in **Chapter 2.3.1**. The wood fibre feedstock processes use a functional unit of 1 kg of wood fibre feedstock on a dry-mass basis.

Land use change emissions are not included for wood fibre feedstocks, since it is assumed that the existing Canadian forest sources require no conversion for bioenergy production in the LCI of wood feedstocks.

Geographical scope for wood fibre feedstock

Forest harvesting data is unavailable at the provincial level. Instead, the LCI for wood fibre feedstocks (merchantable logs, sawmill co-products and sawmill coproduct pellets) is grouped into two regional averages: Eastern Canada and Western Canada, because the Athena Sustainable Materials Institute aggregated data for Eastern Canada and for Canada as a whole. Survey data from these studies included more than 20 sawmills located in Alberta, British Columbia, New Brunswick, Ontario, and Quebec. As such, “Western Canada” represents mills in Manitoba, Saskatchewan, Alberta and British Columbia, while “Eastern Canada” include mills in Newfoundland and Labrador, Nova Scotia, Prince Edward Island, New Brunswick, Quebec and Ontario.

Unmerchantable logs harvest, unmerchantable log chips and unmerchantable log pellets are modelled as Canadian averages.

Allocation for wood fibres production

For the harvesting and production of wood fibres, allocation occurs at the sawmill where sawmilling operations generate several co-products (sawdust, wood chips, bark, shavings, chipper fines and trim ends) aside from lumber. The modelling of sawmill co-products involves allocating the energy consumption (i.e. electricity and fossil fuel use) of sawmill operations based on the mass content of the different sawmill co-products.

Data Sources for wood fibres production

The best publicly available LCI data for primary Canadian forest harvesting operations for merchantable logs 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 five forest harvesting operators for 2015.

The Athena Sustainable Materials Institute studies contain information regarding Eastern and national data. Although no LCA study was available for Western Canada specifically, it was possible to use weighted averages of the Canadian and Eastern Canada datasets to estimate values for Western Canada.

Canadian-specific data was not available for the harvesting of unmerchantable trees which may be harvested as part of a clear cut or during more selective cutting operations such as thinning. The modelling relies on U.S. data from the Consortium for Research on Renewable Industrial Materials in a 2012 LCA study on wood biomass collection and processing in the Southeast United States (Johnson et al., 2012).

For sawmill co-products, the most recent publicly available LCI data for Canadian sawmilling operations is also from the LCA studies carried out by the Athena Sustainable Materials Institute.

The default fuel consumption value for roadside chipping of forest harvest residues and unmerchantable logs is based on a 2012 study of wood biomass energy in Ontario (McKenchie et al., 2012). The default fuel consumption value for roadside chipping of whole trees is assumed to be the same as chipping of harvest residues.

The pelletization process is based on a study of two Quebec’s plants that pelletize sawmill coproduct (Padilla-Rivera et al., 2017). The data from this study are used as a proxy for the pelletization process of chips from unmerchantable logs. The study includes fuel (fossil and biomass) consumption as well as materials used at the pelletization plant.

A summary of the data sources used are listed below.

Merchantable logs harvest and sawmilling (sawdust, wood chips):

- Athena Sustainable Materials Institute. (2018a). A Cradle-to-Gate Life Cycle Assessment of Canadian Surfaced Dry Softwood Lumber
- Athena Sustainable Materials Institute. (2018b). A Cradle-to-Gate Life Cycle Assessment of Eastern Canadian Surfaced Dry Softwood Lumber

Unmerchantable logs and harvest:

- Johnson, L., Lippke, B., & Oneil, E. (2012). Modelling Biomass Collection and Woods Processing Life-Cycle Analysis. *Forest Prod. J. 62(4)*, 258-272

Roadside chipping of unmerchantable logs:

- McKechnie, J. (2012). *Assessing the Greenhouse Gas Emissions Mitigation Potential through the Use of Forest Bioenergy.* Toronto, Ontario: Department of Civil Engineering, University of Toronto

Pelletization process:

- Padilla-Rivera, A.; Barrette, J.; Blanchet, P.; Thiffault, E. Environmental Performance of Eastern Canadian Wood Pellets as Measured Through Life Cycle Assessment. Forests 2017, 8, 352

3.5.6 Raw used cooking oil (UCO) and yellow grease

Modelling approach for yellow grease production from raw UCO

The boundary of the raw UCO process begins with the production of the raw UCO at the restaurants and ends with the restaurant gate. The upstream GHG emissions related to the raw UCO are not included in the dataset since the oil is considered a waste. This process allows Model users to choose raw UCO as feedstock for biodiesel plants that use raw UCO at their facility instead of receiving yellow grease from a rendering plant.

For yellow grease, the boundary of the process begins with the raw UCO at the restaurants and ends with the UCO processing at the rendering facility.

The transport of the raw UCO to the rendering facility considers a trucking distance of 313.6 km calculated using the shares of transportation 1) to rendering plants directly and 2) via a bulk transfer tank before being transported to the rendering plant (GREET 2022). The Model assumes an average payload of 45 tonnes.

UCO processing at the rendering facility includes removing water from the UCO with mechanical and thermal processes. The UCO is assumed to have a water content of 26% based on the amount of raw UCO that is purified to produce 1 kg of yellow grease at the rendering plant (1.35kg). The natural gas and electricity required for remove the water is 2.11 MJ and 0.25 MJ respectively per kg of yellow grease via traditional UCO rendering method, consisting of high-temperature cooking and tricanting (Xu et al. [2022]).

Geographical scope for yellow grease production from raw UCO

The Model includes processes defined at the provincial and national levels for yellow grease production in Canada. Processes only differ in the provincial electricity grid mix used in the purification process. This assumes that the purification process does not differ across Canada, and only the emissions related to electricity differ.

Allocation for yellow grease production from raw UCO

No allocation is required for the production of yellow grease from raw UCO.

Data sources for yellow grease production from raw UCO

- GREET (2022). The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2022)
- Hui Xu, Longwen Ou, Yuan Li, Troy R. Hawkins, and Michael Wang. Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. Environ. Sci. Technol. 2022, 56, 7512−7521

3.6 Fossil fuels

3.6.1 Scope of fossil fuels modelling

The fossil fuel modelling consists of the same life cycle stages presented in **Chapter 2.3**: feedstock production (extraction), feedstock transportation (transmission), fuel production (processing, refining), fuel distribution (transmission, distribution), and fuel combustion (see **Figure 3**). The main processing steps, system boundaries, and final products included in each life cycle stage for gaseous, liquid, and solid fossil fuels in the Model are detailed in the following sections.

The following processes are excluded from calculations of the LCI of fossil fuels:

- Construction and decommissioning of mines, drilling sites, production facilities (e.g. refineries and upgraders
- The manufacturing of fuel transportation infrastructures (i.e., pipelines, trucks, ships, roads) and fuel combustion infrastructure (i.e., vehicles, boilers)
- Oil and gas exploration
- GHG emissions associated with exported fuels
- Research and development activities
- Indirect activities associated with fuel production, such as marketing, accounting, and legal activities
- Land use change related to the extraction stage

The functional unit for fossil fuels is 1 MJ of energy content based on the HHV of each fuel. The LCI for all fuels were calculated from cradle-to-consumer-gate (WTCG) and from cradle-to-combustion.

Given the interconnectivity of the different fossil fuel chain values, allocation methods based on the energy content of fuels was used to allocate impacts between co-products of multifunctional processes (for which there is more than one product).

3.6.2 Modelling approach for gaseous fossil fuels

The main processing steps, system boundaries, and final products included in each life cycle stage for gaseous fossil fuels in the Model are presented in **Figure 10**.

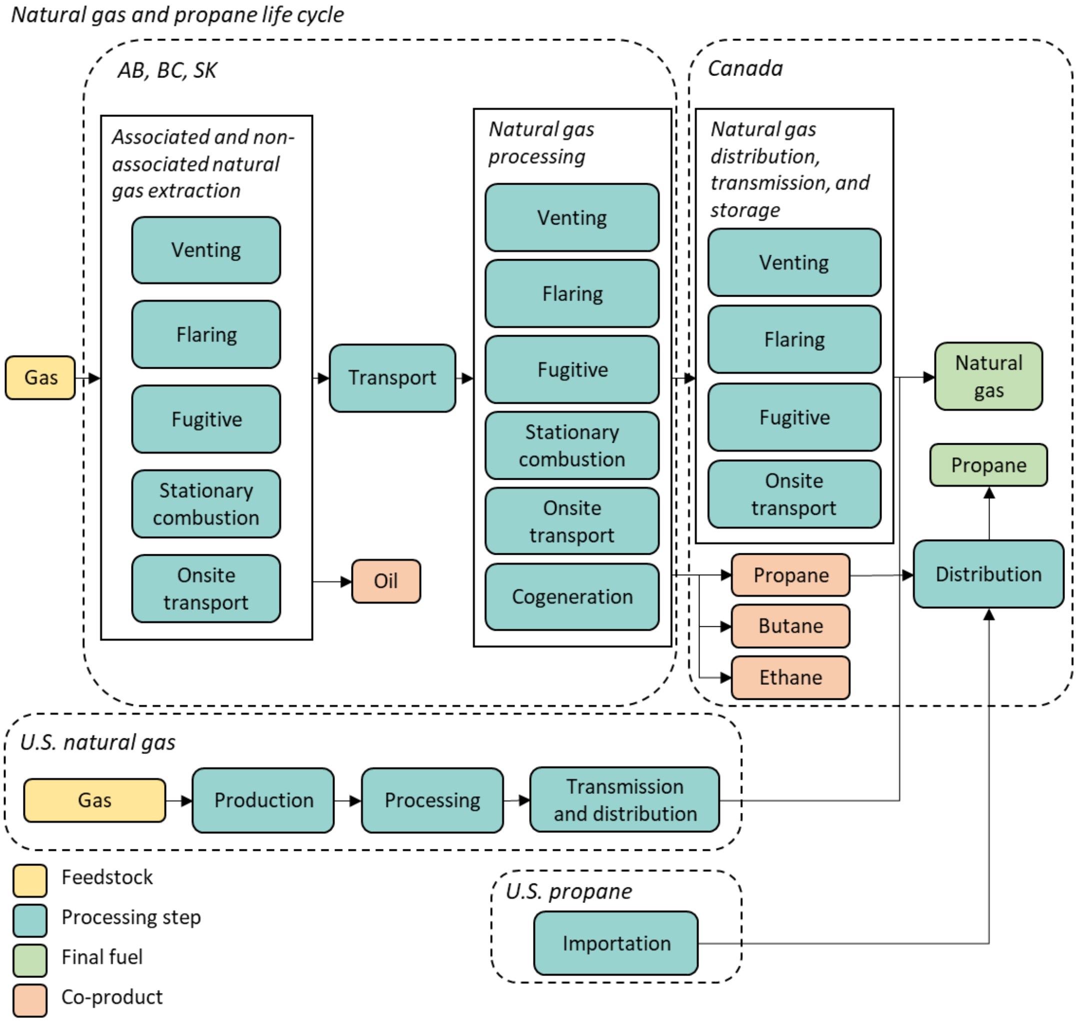

Figure 10: Life cycle stages for gaseous fossil fuels included in the Fuel

Gaseous fossil fuels in the Model refer to natural gas and propane. CNG and LNG rely on the same modelling as natural gas up to their distribution, where there are additional processing steps that are described in **Chapter 3.6.3**.

The methodology for the calculation of the carbon intensity (CI) of natural gas and propane consists of integrating two sets of data. The first set of data is the direct emissions data that are collected from Canada's National Inventory Report (NIR) (published in April 2023, using 2021 data), applying to the oil and gas sector in Canada, and the indirect emissions data that are from other Fuel Life Cycle Analysis (LCA) Model processes. The second set of data is related to production, processing, and marketable volumes of gaseous fuels for 2021, and is collected from Petrinex (Petrinex, 2023) and Statistics Canada databases (Statistic Canada, RESD, 2023).

The CI of natural gas and propane is representative of gaseous fuels consumed in Canada in 2021. The Model assumes that 80% of the natural gas consumed in the country is produced in Canada and the balance is imported from the United States (U.S.) (Natural Resources Canada (NRCan), 2023). For propane, the imported share from the U.S. is about 7% (Statistics Canada, RESD, 2023).

The life cycle stages considered for natural gas CI calculations are extraction, processing, storage, transmission and distribution and combustion. Since propane is a co-product from natural gas processing, the life cycle stages before transmission are identical with natural gas. When electricity and diesel are consumed during the different life cycle stages, the upstream emissions of these inputs are included by using existing datasets from the Model. Emissions from electricity production are modelled at the provincial level for extraction and processing and at the national level for transmission and distribution. The CIs are expressed in grams of CO_2 equivalents (CO_2e) on the basis of one MJ of energy content based on the high heating value (HHV) of natural gas (38.59 MJ/m^3) or propane (25310 MJ/m^3). It is important to note that the HHV of natural gas varied through the life cycle stages, provinces and types of natural gas (associated and non-associated). The different HHV values are listed below.

- Marketable natural gas CA: 38.58 (MJ/m^3) *
- Marketable natural gas US: 40.57 (MJ/m^3) *
- Marketable natural gas AB: 38.82 (MJ/m^3) *
- Marketable natural gas SK: 38.13 (MJ/m^3) *
- Marketable natural gas BC: 38.87 (MJ/m^3) *
- Natural gas at extraction from associated resources AB: 42.31 (MJ/m^3) *
- Natural gas at extraction from associated resources SK: 48.92 (MJ/m^3) *
- Natural gas at extraction from associated resources BC: 42.97 (MJ/m^3) *
- Natural gas at extraction from non-associated resources AB: 41.53 (MJ/m^3) *
- Natural gas at extraction from non-associated resources SK: 40.59 (MJ/m^3) *
- Natural gas at extraction from non-associated resources BC: 42.17 (MJ/m^3) *
- Conventional light oil: 38800 (MJ/m^3) *
- Propane liquid: 25310 (MJ/m^3) **
- Ethane liquid: 17220 (MJ/m^3) **
- Butane liquid: 28440 (MJ/m^3) **

*ECCC, NIR 2023; **Statistics Canada, RESD, 2023

The following sections describe the domestic natural gas and propane modelling for Canada and the US.

Canadian gaseous fuels

Extraction of gaseous fuels

For the domestic production, the Model considers production of raw gas from associated (conventional oil sector) and non-associated gas resources in Alberta (AB), British Columbia (BC), and Saskatchewan (SK). This represents more than 95% of the total Canadian gaseous fuel production. Therefore, Canadian CI cradle-to-gate is a weighted average of extraction and processing CI based on produced and processed volumes in each province.

For extraction, natural gas is extracted from two types of wells: the non-associated well, which mainly produces natural gas and the conventional light oil well, which produces oil and gas simultaneously.

Extraction volumes of raw gas and oil (for energy allocation) at the provincial level are from Petrinex (2023). The volumes are then converted to energy with the HHV specific to the province and type of resource

Two other types of wells or natural gas sources in Canada, heavy oil extraction sites and thermal oil extraction sites, are not considered because it is assumed that they do not contribute significantly to the production of marketable gas in Canada.

Extraction emissions include emissions that may occur before well exploitation, during well drilling, and after wells are closed. For each type of well, the main categories of direct emissions are fugitive, venting, flaring, stationary combustion and onsite transport (i.e., diesel use). Emissions from the production of electricity used by the natural gas production sector are also considered.

Processing of gaseous fuels

Processing modelling is based on gas plants located in Alberta, British Columbia and Saskatchewan. Processing volumes of natural gas and natural gas liquids at the provincial level are identified with marketable volumes at the provincial level. The data comes from Statistics Canada, Table 25-10-0055-01. They are then converted to energy with the HHV specific to the province The national processing volume is the sum of the three provinces and represents more than 98% of the Canadian marketable natural gas output.

The processing scope covers sulfur recovery, sweet gas and acid flaring. The main categories of emissions that are included are fugitive, venting, flaring, stationary combustion and industrial cogeneration. Emissions from the production of electricity used by the natural gas processing sector are also considered.

U.S. gaseous fuels

The US CI of natural gas and propane in the Model is based on the GREET model values for the hybrid pathway (GREET, 2022). It includes production, processing, transmission and distribution.

In the GREET model, emissions are provided by British Thermal Unit (BTU) low heating value (LHV) and the quantities of energy have been converted to HHV based on the conversion factors available in the U.S. model.

U.S. natural gas

Total U.S. production is divided between conventional (25%) and shale gas (75%). The production stage includes emissions from flaring, venting, leakage and stationary combustion. The processing stage includes these same sources of emissions in addition to non-combustion emissions. Transmission and distribution include emissions from venting, leakage and stationary combustion only. Losses are considered between upstream stages and transmission and distribution (approximately 0.3%).

U.S. propane

In the U.S., propane is a coproduct of both the oil and natural gas supply chain in a 14% to 86% ratio. Emissions linked with extraction and gathering of these feedstocks to produce propane are included in the U.S. CI, as well as propane production and transmission emissions.

Transmission, storage and distribution of gaseous fuels

In the NIR, transmission and storage emissions for natural gas are taken at the national level and gathered under the same sector of emissions. This report covers emissions for the natural gas transported from the processing plants in Canada or from the border with the U.S.to the gate of the local distribution systems by high-pressure pipelines. The NIR includes emissions from normal operation, but also accidental releases. It includes emissions from delivering and withdrawing from storage. The main categories of emissions that are included are fugitive, venting, flaring and onsite transport. Emissions from the production of electricity used by the natural gas transmission and storage sector are also considered.

The volume of natural gas is taken from Statistics Canada (Table 25-10-0055-01). The imported volume from the U.S. is added to the Canadian marketable natural gas. The resulting volume is then converted to energy with Canadian and U.S. average HHV.

Distribution refers to the activity of delivering natural gas to the final consumer. Pressure of pipeline is cut down from the transmission grid and the meshing is denser. It includes emissions due to normal operation, but also accidental releases. The same categories of emissions for transmission and storage are considered.

The volume of natural gas is taken from Statistics Canada (Table 25-10-0055-01). The volume exported to the U.S. is subtracted from the sum of Canadian marketable natural gas and U.S. imports. The resulting volume is then converted to energy with Canadian and U.S. average.

Allocation of gaseous fuels

Energy allocation is performed to allocate emissions to the natural gas system where co-production occurs: associated extraction (oil and natural gas) and natural gas processing (ethane, propane, butane and natural gas).

Data sources for gaseous fuels

The data sources used for gaseous fuel modelling are shown below.

Emissions of natural gas supply chain in Canada:

- Environment and Climate Change Canada, Greenhouse Gas Division, (Publish April 2023 with 2021 data), National inventory report :greenhouse gas sources and sinks in Canada: ISSN: 1910-7064

Emissions of natural gas supply chain in the U.S.:

- Argonne National Laboratories, 2022, GREET, Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model. Accessible: Argonne GREET Model (anl.gov)

Volumes of produced, marketable, imported and exported natural gas and propane:

- Petrinex 2023, Home (used data from 2021)
- Statistics Canada. Table 25-10-0055-01 Supply and disposition of natural gas, monthly (data in thousands) (x 1,000)

Share of importation for natural gas and propane in Canadian consumption mix:

- Natural Resources Canada 2023, Energy Fact Book 2022-2023 (PDF)
- Statistics Canada 2023, Report on Energy Supply and Demand in Canada (RESD): Explanatory Information

3.6.3 Modelling approach for liquid and solid fossil fuels

Efforts to model in a consistent way across all fuels were made despite the differences in tools and data available. Wherever possible, Canadian-specific data that reflects 2016 fossil fuel production operations were used. In addition, once modelling and data uncertainties are considered, the cradle-to-combustion CIs for Canadian, American[28] and European[29] fossil fuels do not show significant differences. Hence, the approach for the internationally produced fossil fuels is to treat their CI as equivalent to Canadian produced fossil fuels.

The main processing steps, system boundaries, and final products included in each life cycle stage for liquid, and solid fossil fuels in the Model are presented in **Figure 11**, dashed lines represent co-products transferred between liquid and solid fossil fuel life cycle stages. Note that special process routes and other co-products are not represented.

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[28] Gregory Cooney, Matthew Jamieson, Joe Marriott, Joule Bergerson, Adam Brandt, and Timothy J. Skone. Environmental Science & Technology 2017 51 (2), 977-987

[29] BioGrace-I GHG calculation tool – version 4d.

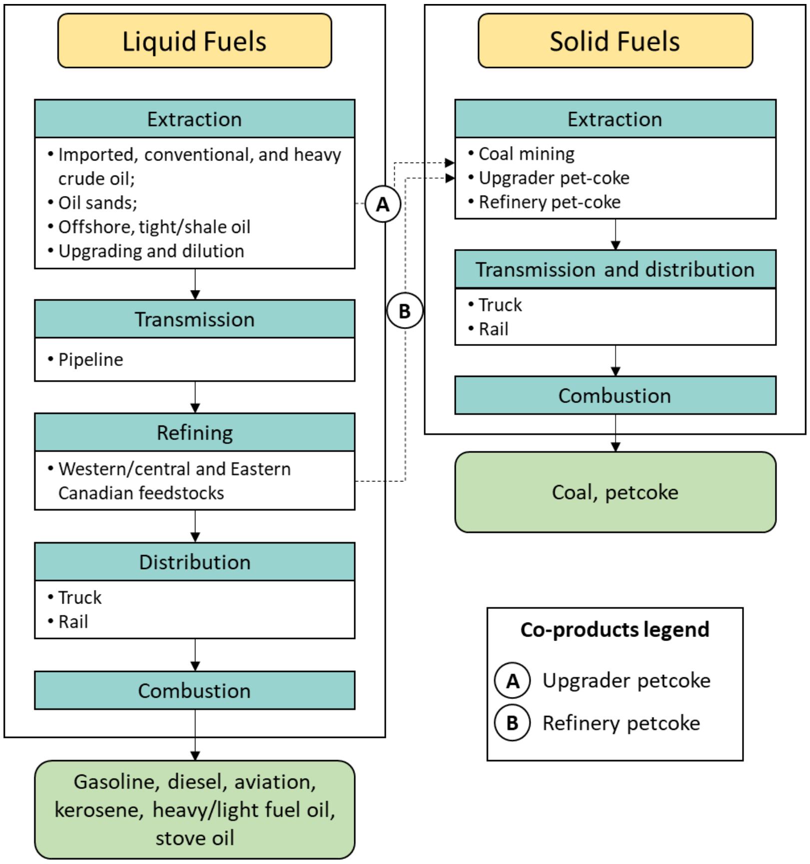

Figure 11: Life cycle stages for liquid and solid fossil fuel.

The following sections summarize the modelling approach taken for liquid, and solid fossil fuels.

Liquid fuels

Crude oil for refining in Canada originates from several sources: conventional crude, oil sands mining and upgrading, oil sands in-situ (and heavy crude via steam-assisted gravity drainage), offshore extraction, and imports from countries outside of Canada. Each of these feedstock sources was considered in developing the dataset for fossil fuels in the Model. While crude oil extraction occurs in many provinces within Canada, 95% of domestic production primarily takes place in Alberta and Saskatchewan. The Model also considered crude oil imports from the U.S. and other international sources, which represent of 33% of domestic consumption.

Extracted crudes are transported via pipeline to refineries distributed in Eastern and Western Canada. Canadian oil and gas market reports, and facility production data, were used to identify the extraction and pre-processing methods relevant to the Canadian industry. CI results were aggregated based on the source locations of crude products (e.g., Eastern and Western Canada, and imports) and the refinery types. In this sense, each refinery product (e.g. aviation fuel, diesel, gasoline, kerosene, etc.) was modelled for Eastern and Western/Central Canada; Canadian pathways were derived based on the production-weighted average of both regions.

Extraction of liquid fuels

Distinct extraction models were developed for each Canadian oil source: conventional crude, oil sands mining and upgrading, oil sands in-situ, and offshore extraction. The modelling was conducted using the Oil Production Greenhouse Gas Emissions Estimator (OPGEE), an engineering-based model that estimates GHG emissions from the production, processing, and transport of crude oil, based on data from Canadian facilities. Government information on technology pathways and operating parameters were sourced from Alberta Energy Regulator, the NEB and Statistics Canada. The CIs of crude oil imports from other countries were based on data from the NEB and the Oil Climate Index.[30] An average CI was calculated for imported crudes based on import shares (%) between the different countries. Venting and flaring emissions from oil extraction were modelled using actual reported facility level data when available. Emissions were allocated to other fuels produced during oil extraction, including natural gas liquids (NGL) (associated gas) and upgrader petcoke, by using an energy-based allocation procedure and are not considered in the fossil fuel CI values.

Refining of crude to liquid fuels

Thirteen of the sixteen Canadian refineries were modelled in detail based on 2016 data from Woods Mackenzie as well as the Petroleum Refinery Life Cycle Inventory Model (PRELIM). The refinery products from Wood Mackenzie were matched with PRELIM's product slate. PRELIM was used to model a mass- and energy-based representation of the refining process and calculate GHG emissions for refined products (e.g. blended gasoline, jet fuel, ultra-low sulfur diesel, fuel oil, coke, liquid heavy ends, liquefied petroleum gas, etc.). Both the OPGEE and PRELIM models are unique in that they offer the ability to model the respective processes in detail for a specific facility or refinery. The refining processes for each of these products were defined for Eastern and Western Canada. In addition, results from the PRELIM model were compared to data available in the Canadian Greenhouse Gas Reporting Program (GHGRP). Once the results from each tool were adjusted to ensure a comparable scope, results were generally consistent.

Transmission and distribution of liquid fuels

Crude transport in pipelines across Canada was modelled by estimating distances between oil reservoirs, production facility and refineries using a combination of Canadian data and published literature. Transport of imported crudes was modelled using Canada's National Marine Emissions Inventory Tool (MEIT)[31].

In the Model, it is assumed that there is no difference in energy requirements for the transport of crude oil, bitumen and diluent. The LCI for liquid pipeline transport was calculated based on the amount of electricity used to power the pipelines pumps based on energy intensity data from Choquette-Levy et al (2018).

Production of compressed natural gas (CNG) and liquefied natural gas (LNG) were modelled based on the assumption that up until the point of compression or liquefaction, the life cycles of CNG and LNG are

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[30] OCI, 2018. Oil Climate Index.

[31] Environment and Climate Change Canada. 2019. Marine Emissions Inventory Tool.

the same as pipeline specification natural gas. The fuel types for natural gas and LNG transportation and storage are shown below.

Pipelines (gas)

- Natural gas and electricity

Geological Storage

- Natural Gas

Liquid natural gas storage

- Liquid natural gas

The compression step associated with CNG production was modelled using data from GREET and the California Air Resources Board (CARB). The GHG emissions related to the liquefaction process were modelled using a Canadian study on LNG.[32] The main data sources used for the modelling of gaseous pipeline transportation are shown below.

Pipeline:

- Choquette-Levy, N., M. Zhong, H. MacLean, J. Bergerson, 2018, COPTEM: A Model to Investigate the Factors Driving Crude Oil Pipeline Transportation Emissions. Environmental Science & Technology. 52, 337–345

Solid fuels

The LCI of petcoke was modelled based on results from both OPGEE and PRELIM to reflect the amount of petcoke that is produced and used from both upgrading and refining. Imported petcoke was assigned the same CI value as Canadian domestic petcoke.

For coal, the extraction stage, which was assumed to occur entirely in Western Canada, was based on 2012 data from a study by Cheminfo Services Inc. on coal mining.[33] The scope of the analysis for coal was limited to thermal coal, including bituminous, sub-bituminous, and lignite coal. The dataset for imported coal from the U.S. was obtained from the GREET tool by Argonne National Laboratories.

3.6.4 Combustion emission factors for fossil fuels

Emission factors related to combustion were based on the NIR. For cases where multiple emissions values were reported for fuels based on their origin of production, a single combustion value was calculated based on the production-weighted average of each of these fuels. Although useful energy generated from fuel combustion varies depending on the efficiency of the combustion device, the

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[32] Sapkota, K., A. O. Oni, and A. Kumar, 2018: Techno-economic and life cycle assessments of the natural gas supply chain from production sites in Canada to north and southwest Europe. Journal of Natural Gas Science and Engineering, 52, 401–409, doi:10.1016/j.jngse.2018.01.048.

[33] Cheminfo Services Inc. & Clearstone Engineering Ltd. 2014. Compilation of a National Inventory of Greenhouse Gas and Fugitive VOC Emissions by the Canadian Coal Mining Industry. Final Report, March 31, 2014. Prepared for Environment Canada. Solicitation K8A42-12-0012.

modelling of CI values for specific combustion types and devices (e.g., heating, transportation, and electricity) was beyond the scope of this project. As such, a single combustion emission factor per fuel based on HHV was applied to calculate the CI.

3.7 Renewable fuels

The Data library includes three renewable fuels that can be used as a fuel input in the modelling of a fuel pathway. These datasets cover the cradle-to-combustion life cycle stages of these fuels.

3.7.1 Combusted renewable fuels

Combusted renewable fuels are modelled using two feedstock sources: wood fibres (sawmill co-products) and agricultural residues. The modelling for each feedstock production is detailed in **Chapter 3.5.4** and **Chapter 3.5.3**, respectively**.** The table below summarizes the renewable fuel combustion processes included based on feedstock and fuel production type.

Table 6: List of feedstocks and conversion processes included in the Model for combusted renewable fuels

Feedstock	Fuel production process	Fuel
Sawmill co-products	None	Wood chips
Sawmill co-products	Pelletization	Wood pellets
Agricultural residues	Densification	Agricultural residue pellets

Modelling approach for wood chips and wood pellets combustion

The Model includes the conversion of wood fibre feedstocks into solid renewable fuels. This group of fuels includes wood chips and wood pellets from sawmill co-products. These processes model the LCI for renewable fuel combustion, which is visualized in **Figure 12**.

The cradle-to combustion datasets are based on a functional unit of 1 MJ of energy content based on the HHV delivered to the end user and used for its energy content.

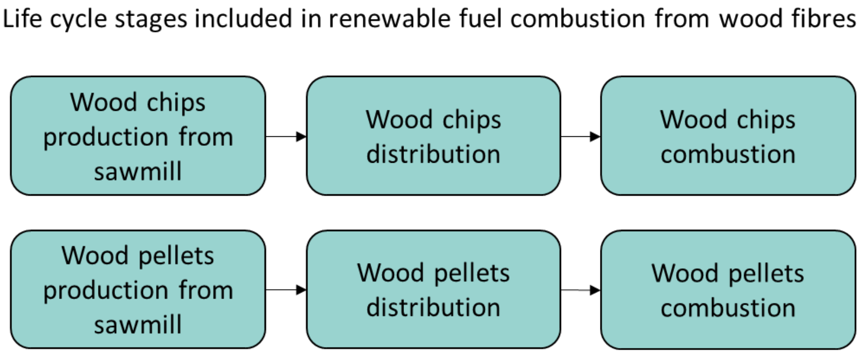
Life cycle stages included in renewable fuel combustion from wood fibres

Figure 12: Life cycle stages for renewable fuels based on wood fibre included in the Model

The modelling of distribution to end users is a function of the moisture content equivalent to market level content. **Table 7** summarizes the moisture content of solid renewable fuels included in the Model, as well as the corresponding HHV based on data from Natural Resources Canada (*Solid Biofuels Bulletin No. 2 Primer for Solid Biofuels*). For both types of fuels, it is assumed that the HHV on dry mass basis is

21.5 MJ/kg. A distance of 100 km by truck is assumed for transportation between the sawmill and the end user.

Table 7: Moisture content of solid renewable fuels and corresponding high heating values (MJ/kg)

Renewable fuels	Moisture content (%)	HHV (MJ/kg)
Wood chips from sawmill	45%	10.5
Wood pellets from sawmill co-products	10%	19

CH_4 and N_2O emissions from the combustion process is modelled with emission factors from the NIR for two general applications: combustion of wood chips in industrial furnaces and combustion of wood pellets in residential pellet stoves. Biogenic CO_2 emissions are not included in the modelling.

Geographical scope for wood chips and wood pellets combustion

Fuel production processes were modelled to be representative of a Canadian national average process, using a 50/50 mix of sawmill co-products from Western and Eastern Canada. More information on the geographical scope of the wood pellets and chips from sawmills is available in **Chapter 3.5.5**. These processes can be used regardless of geographical location.

Allocation for wood chips and wood pellets combustion

Allocation procedure for the cradle-to-sawmill gate life cycle stages are explained in **Chapter 3.5.5**. No other allocation procedure was performed for solid renewable fuel produced from wood fibres.

Data sources for wood chips and wood pellets combustion

Data sources for the cradle-to-sawmill gate life cycle stages are presented in **Chapter 3.5.5**.The combustion process is based on the NIR (2018). The data sources for distribution and combustion life cycle stages are listed below.

Distribution (moisture content) and HHV:

- Natural Resources Canada. Solid Biofuels Bulletin No. 2

Combustion:

- Government of Canada. (2018). National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada

Modelling approach for agricultural residue pellets combustion

The Model includes a system process that models the combustion of pellets produced from agricultural residues. The process covers the collection of harvest residues and transportation to a densification unit where residues are converted into pellets before being transported to the final user and combusted.

The agricultural residues collection process is explained in **Chapter 3.5.3**. The production process involves the densification of agricultural residues to produce agricultural residue pellets, which are used much like wood pellets from wood fibre conversion. The densification process generally includes a series of steps including receiving bales of residues, grinding, pelletizing, cooling, and screening. The process was modelled by including electricity and fossil fuel inputs for the pelletization process, as well as for the other steps. **Figure 13Figure 13** outlines the scope of the agricultural residue pellets combustion dataset. The dataset is based on a functional unit of 1 MJ of agricultural residue pellets HHV delivered to the end user.

The modelling of the densification process relies on Canadian data for the densification of wheat straw. As such, it is assumed that agricultural residue feedstocks, would undergo the same densification process.

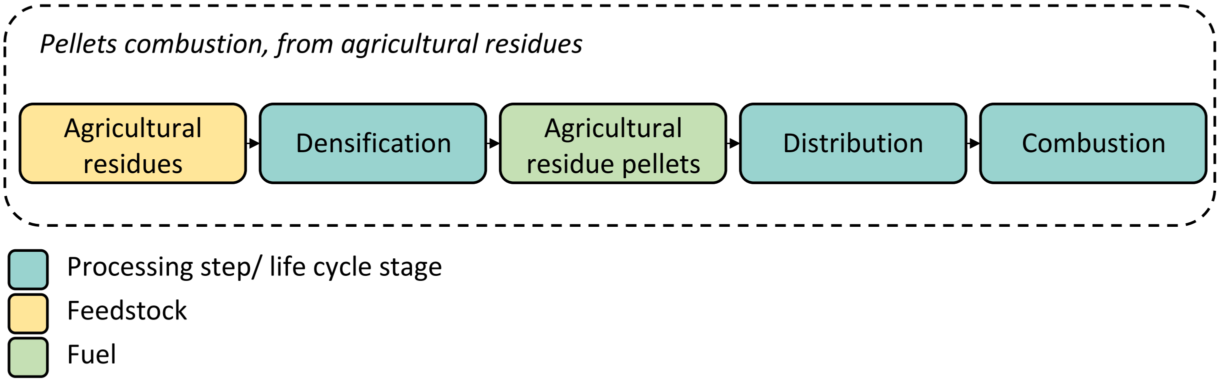

Figure 13: Processing overview for the combustion of agricultural residue pellets

The modelling of transportation to the densification plant and subsequent distribution to end user is a function of the moisture contents of the residues and the pellets and they are assumed to be respectively at 11.9% and 9%. The distances between the farm and the densification plant, and between the densification and the end user are both 100 km by truck. CH_4 and N_2O emissions are included based on the emission factors for wood fuel combustion in an industrial furnace from Canada's NIR. Biogenic CO_2 emissions are not included in the modelling.

Geographical scope for agricultural residue pellets combustion

The production process was modelled at the Canadian national level using data from a 2012 LCA study focusing on the densification of wheat straw pellets in the Canadian Prairies (Li X. et al., 2012). The geographical scope for the cradle-to-farm gate life cycle stages is presented in in **Chapter 3.5.3**. This system process can be used regardless of geographical location.

Allocation for agricultural residue pellets combustion

The allocation procedure for the cradle-to-farm gate life cycle stages is explained in **Chapter 3.5.3**. No other allocation procedure was performed for solid renewable fuel produced from crop residues.

Data Sources for agricultural residue pellets combustion

Data sources for the cradle-to-farm gate life cycle stages are presented in **Chapter 3.5.3**. The production process and moisture content relied on data from a 2012 LCA study focusing on the densification of wheat straw pellets in the Canadian Prairies (Li X. et al., 2012). As mentioned, it is assumed that the densification process stays the same regardless of the type of agricultural residue feedstock. The combustion process is based on the NIR (2018) and the HHV for agricultural residues are taken from the GREET Model. The main data sources used in the densification process are listed below.

Densification process:

- Li, X., Mupondwa, E., Panigrahi, S., Tabil, L., & Adapa, P. (2012). Life cycle assessment of densified wheat straw pellets in the Canadian Prairies. *International Journal of Life Cycle Assessment 17*, 420-431

HHV:

- GREET (2018). The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2018)

Combustion:

- Government of Canada. (2018). National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada

3.8 Transport

3.8.1 Generic transport

There are four generic modes of transportation and distribution included in the Model presented below:

Truck
Rail
Ship
Gas pipeline

The fuel used for each process is as follows:

- Truck: Diesel
- Train: Diesel
- Tanker ship: Marine diesel oil and heavy fuel oil
- Gas pipeline: Natural gas and electricity

As the fossil fuel consumption of each transport process is directly linked to the mass transported and the distance travelled, the functional unit of transport system processes in the Model is 1 tonne-kilometre (tkm - i.e. transport of one metric tonne of feedstock or fuel over a distance of one kilometer). The transport processes considered the amount of fossil fuel consumed per tkm of transport. As stated in **Chapter 2.3.1**, the manufacturing of fuel transport infrastructure (i.e., pipelines, trucks, ships, and roads) was excluded from the Model.

Modelling approach for generic transportation

Fuel consumption data was gathered for each mode of transportation using Canadian and U.S. statistics as well as literature data. Each sub-section describes the modelling approach taken for that mode of transportation, with the main references listed in the following subsections.

Train transport

The amount of diesel consumed per tkm of train transport was based on 2021 data from the Rail Association of Canada on the freight mass, the distance travelled and the annual quantity of diesel consumed.

The main data source used is listed below:

- Rail Association of Canada. (2023). Locomotive emissions monitoring report (PDF)

Truck transport

The truck's diesel consumption is directly related to the mass transported and the distance traveled.

The Model assumes B Train trucks are used for generic truck transport. The fuel consumption factor modeled for B Train trucks is 60.98 L/100km. This factor considers the fuel efficiency for full trucks of 50 L/100km, averaged from multiple sources (NRCan, 2000; Kabir and Kumar, 2012), an empty fuel consumption ratio of 0.6097 (Kabir and Kumar, 2012), the distance travelled empty between loads of 26% from the American Transportation Research Institute (ATRI, 2021), and the payload.

There are two generic truck transport processes. The truck transport payload of 45 tonnes is determined by using the maximum weight of a truck (CoMT, 2019) and the average weight of an empty truck (Onsite, 2022). The truck transport payload of 25 tonnes is determined by using data from the 2023 GREET model.

This process is considered representative of transport by truck in North America. Some data was sourced from U.S. references. The processes can be used regardless of geographical location.

The main data sources used are listed below:

- CoMT. (2019). Heavy Truck Weight and Dimension Limits for Interprovincial Operations in Canada. Category 3: B Train Double, Part 2 - Weight Limits
- GREET (2023). The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2023). Tab 'T&D'. 1) Cargo Payload By Transportation Mode and by Product Fuel Type: Tons. Row 7
- Kabir and Kumar. (2012). Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. Table 3: Inventory data for biomass transportation in different forms
- Leslie, A. and Murray, D. (2021). An Analysis of the Operational Costs of Trucking. American Transportation Research Institute (ATRI)
- Onsite, Truck and Equipment Repair. (2022). How much does a semi truck weigh? Ultimate guide
- NRCan. (2000). Fuel Efficiency Benchmarking in Canada's Trucking Industry. Fuel Efficiency: Page 3
- Sultana and Kumar. (2011). Optimal configuration and combination of multiple lignocellulosic biomass feedstocks delivery to a biorefinery. Table 3: Weight carried by trucks for various forms of biomass (Payload of truck = 22.7 tonnes, Volume capacity of truck = 70 m3)

Ship transport

The process modelling is based on the 2018 fuel consumption data and Efficiency Operational Indicator (EEOI) data taken from the International Marine Organization's (IMO) Fourth Greenhouse Gas Study published in 2020 (table 35 and 60 respectively).

The modeling considers EEOI and fuel consumption for the following ship types: bulk carrier, container ship, general cargo ship, chemical tanker, and oil tanker. The EEOI is used to model direct emissions while fuel consumption is used to model the amount of energy required for the transport (for upstream emissions). The amount of fuel consumed (assumed to consist entirely of marine diesel oil (MDO) and heavy fuel oil (HFO) oil) per tonne of cargo * km traveled is calculated using the vessel-based approach. The shares of fuel consumption attributed to HFO and MDO were distributed based on 2017 fuel consumption by fuel type and light fuel oil (LFO) is used in the Model as a proxy for MDO.

Direct emissions and energy requirement for the process are calculated by taking a weighted average of EEOI and fuel consumption respectively of ship types, where the weighted average for each ship type is calculated by taking a weighted average of the EEOI and fuel consumption by size category.

The main data source used is listed below:

- International Maritime Organization (IMO). (2020). International Marine Organization (IMO) Fourth Greenhouse Gas Study 2020

Gas Pipeline transport

The amount of energy consumed per tkm of gas pipeline transport was based on 2022 GREET model. Weighted average energy to transport 1 MJ over a distance of 1 km by pipeline was used to model the energy use. Natural gas is responsible for the 98% of the energy needed for pump operations. The remainder is assumed to be coming from electricity. Canadian grid electricity is used to reflect the emissions due to the average electricity usage across Canada.

Flaring, fugitive, venting and emergency response emissions were included to calculate the CI of natural gas transport. The 2021 reference year data collected for 2023 Canada's National Inventory Report (NIR, 2023) is used to quantify fugitive, venting and flaring emissions from natural gas pipelines.

This process is considered representative of transport by pipeline in Canada. However, some data was sourced from U.S. references. The processes can be used regardless of geographical location.

The main data sources used are listed below:

- GREET (2022). The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2022)
- Government of Canada. (2023). National Inventory Report 1990-2021: Greenhouse Gas Sources and Sinks in Canada

3.8.2 Hydrogen transport

Transportation of hydrogen covers the transport of 1 tkm of hydrogen. The hydrogen transportation processes available in the Model provided are the following:

- Truck transport, of liquid hydrogen
- Truck transport, of gaseous hydrogen
- Pipeline transport, of hydrogen, injected in natural gas pipeline
- Pipeline transport, of hydrogen, dedicated pipeline

Modelling approach for hydrogen transportation

The following sections describe the modelling for hydrogen transportation based on mode of transportation. No allocation procedures were performed while modelling the transportation of hydrogen.

Truck transport

The truck's diesel consumption is directly related to the mass transported and the distance travelled.

The Model assumes heavy-duty trucks other than B Train trucks are used for hydrogen truck transport. The fuel consumption factor modeled for heavy-duty trucks is 69.09 L/100km. This factor considers the fuel efficiency for full trucks of 40 L/100km, averaged from multiple sources (NRCan, 2000; Kabir and Kumar, 2012), an empty fuel consumption ratio of 0.7273 (Kabir and Kumar, 2012), and the payload.

It also assumes that transporting compressed and cooled fuels requires specialized equipment, limiting the type of material the truck can transport and requires the trucks to travel further while empty. A worst-case scenario is assumed, with 50% of the distance is being travelled empty between loads, as emptied trucks will return directly to their origin for another load.

Truck transport average payloads are based on GREET 2022 and are 3.6 tonnes for liquid hydrogen and 1.0 tonne for gaseous hydrogen.

These processes are intended to be representative of truck transport of hydrogen in North America. Some data was sourced from US references. The processes can be used regardless of geographical location.

The main data sources used are listed below:

- GREET 2022 model. Tab T&D. 1) Cargo Payload By Transportation Mode and by Product Fuel Type: Tons Cell Q7 Gaseous Hydrogen and R7 Liquid Hydrogen. Retrieved from: Argonne National Laboratory
- Kabir and Kumar. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. 2012. Table 3: Inventory data for biomass transportation in different forms. Retrieved from: Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways
- NRCan. Fuel Efficiency Benchmarking in Canada's Trucking Industry. March 2000. Fuel Efficiency: Page 3. Retrieved from: National Resources Canada, FleetSmart

Dedicated pipeline and transport in natural gas pipeline

For hydrogen transport using natural gas pipelines, the 2022 GREET model for natural gas pipeline modelling has been used as a proxy. Weighted average energy to transport 1 MJ over a distance of 1 km by pipeline was used to model the energy use. Natural gas is responsible for the 98% of the energy needed for combustion. The remainder is assumed to be coming from electricity. Canadian average grid is applied to reflect the emissions due to the average electricity usage across Canada.

For hydrogen transported in a dedicated pipeline, it has been assumed that 100% of the energy requirements are met by electricity from grid. Energy input data is based on the 2022 GREET model.

The main data sources used are listed below:

- Ramsden, T., Ruth, M., Diakov, V., Laffen, M., & Timbario, T. A. (2013). Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios
- GREET 2022 model. Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89. Retrieved from: Argonne National Laboratory

3.8.3 Natural gas transport

Modelling approach for natural gas transportation

Transport of 1 tkm of liquefied natural gas (LNG) and liquefied renewable natural gas (liquefied RNG) in Canada was modelled using pipelines and diesel trucks.

The following sub-sections describe the modelling approach taken for each of these modes of transportation.

Truck transport, liquefied natural gas and RNG

The truck's diesel consumption is directly related to the mass transported and the distance traveled.

The Model assumes heavy-duty trucks other than B Train trucks are used for both LNG and RNG truck transport. The fuel consumption factor modeled for heavy-duty trucks is 69.09 L/100km. This factor considers the fuel efficiency for full trucks of 40 L/100km, averaged from multiple sources (NRCan, 2000; Kabir and Kumar, 2012), an empty fuel consumption ratio of 0.7273 (Kabir and Kumar, 2012), and the payload.

It also assumes that transporting compressed and cooled fuels requires specialized equipment, limiting the type of material the truck can transport and requires the trucks to travel further while empty. A worst-case scenario is assumed, with 50% of the distance is being travelled empty between loads, as emptied trucks will return directly to their origin for another load.

The average LNG payload from GREET 2022 are used for both LNG transport and as a proxy for liquified RNG at 13.6 tonnes.

Boil-off emissions during truck transport of LNG from GREET 2022 are used as a proxy for the transport of liquefied RNG.

This process is intended to be representative of both LNG and liquefied RNG in North America. Most data was sourced from U.S. references. The processes can be used regardless of geographical location.

The main data sources used are listed below:

- Kabir and Kumar. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. 2012. Table 3: Inventory data for biomass transportation in different forms. Retrieved from: Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways
- GREET (2022). The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2022). Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89
- GREET (2022). The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2022). Tab 'NG'. 3) Calculations of Energy Consumption, Water Consumption, and Emissions for Each Stage: Total emissions: grams/mmBtu of fuel throughput. Cell AM67
- NRCan. (2000). Fuel Efficiency Benchmarking in Canada's Trucking Industry. March 2000. Fuel Efficiency: Page 3. Retrieved from: National Resources Canada, FleetSmart

Truck transport, compressed natural gas and RNG

The truck's diesel consumption is directly related to the mass transported and the distance traveled.

The Model assumes heavy-duty trucks other than B Train trucks are used for CNG and compressed RNG truck transport. The fuel consumption factor modeled for heavy-duty trucks is 69.09 L/100km. This factor considers the fuel efficiency for full trucks of 40 L/100km, averaged from multiple sources (NRCan, 2000; Kabir and Kumar, 2012), an empty fuel consumption ratio of 0.7273 (Kabir and Kumar, 2012), and the payload.

It also assumes that transporting compressed and cooled fuels requires specialized equipment, limiting the type of material the truck can transport. A worst-case scenario is assumed, with 50% of the distance is being travelled empty between loads, as emptied trucks will return directly to their origin for another load.

The average payload for CNG is 6 tonnes and is used as a proxy for compressed RNG[34].

Boil-off emissions during truck transport are based on 2022 GREET model and used as a proxy for CNG and compressed RNG.

These processes are considered to be representative of truck transport of CNG and compressed RNG in North America. Most data were sourced from U.S. references. The processes can be used regardless of geographical location.

The main data sources used are listed below:

- Kabir and Kumar. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. 2012. Table 3: Inventory data for biomass transportation in different forms. Retrieved from: Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways

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[34] Based on internal communication with Transport Canada (May 2023)

- GREET 2022 model. Tab 'NG'. 3) Calculations of Energy Consumption, Water Consumption, and Emissions for Each Stage: Total emissions: grams/mmBtu of fuel throughput. Cell AM67. Retrieved from: Argonne National Laboratory
- NRCan. Fuel Efficiency Benchmarking in Canada's Trucking Industry. March 2000. Fuel Efficiency: Page 3. Retrieved from: National Resources Canada, FleetSmart

Pipeline transport, RNG

The amount of energy consumed per tkm of renewable natural gas (RNG) pipeline transport is based on 2022 GREET model, using natural gas pipelines as a proxy.

Weighted average energy to transport 1 MJ over a distance of 1 km by pipeline was used to model the energy use. RNG is responsible for the 98% of the energy needed for pump operations. The remainder is assumed to be coming from electricity. Canadian average grid is applied to reflect the emissions due to the average electricity usage across Canada.

Flaring, fugitive, venting and emergency response emissions were included to calculate the CI of RNG transport. The 2021 reference year data collected for 2023 Canada's National Inventory Report (NIR, 2023) is used to quantify fugitive, venting and flaring emissions from RNG pipelines, using natural gas as a proxy.

This process is considered to be representative of pipeline transport of RNG in Canada. However, some data was sourced from U.S. references. The processes can be used regardless of geographical location.

The main data sources used are listed below:

- GREET (2022). The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2022). Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89
- Government of Canada. (2023). National inventory report : greenhouse gas sources and sinks in Canada

3.8.4 Propane transport

Modelling approach for propane transportation

Transport of 1 tkm of propane and renewable propane in Canada was modelled for pipelines and diesel trucks.

The following subsections describes the modelling approach for each of these transportation modes.

Truck transport, liquid propane

The truck's diesel consumption is directly related to the mass transported and the distance traveled.

The Model assumes B train trucks are used for liquid propane transport. The fuel consumption factor modeled for B Train trucks is 60.98 L/100km. This factor considers the fuel efficiency for full trucks of 50 L/100km, averaged from multiple sources (NRCan, 2000; Kabir and Kumar, 2012), an empty fuel consumption ratio of 0.6097 (Kabir and Kumar, 2012), the distance travelled empty between loads of 26% from the American Transportation Research Institute (ATRI, 2021), and the payload.

The average payload for propane is 25 tonnes[35].

Fugitive propane emissions are not considered.

This process is considered to be representative of liquid propane by truck in North America. Most data was sourced from U.S. references. The processes can be used regardless of geographical location.

The main data sources used are listed below:

- Kabir and Kumar. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. 2012. Table 3: Inventory data for biomass transportation in different forms. Retrieved from: Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways
- Leslie, A. and Murray, D. An Analysis of the Operational Costs of Trucking: 2021 Update. November 2021. American Transportation Research Institute (ATRI). Retrieved from: An Analysis of the Operational Costs of Trucking: 2021 Update (PDF)
- NRCan. (2000). Fuel Efficiency Benchmarking in Canada's Trucking Industry. March 2000. Fuel Efficiency: Page 3. Retrieved from: National Resources Canada, FleetSmart

Pipeline transport of liquid renewable propane

The amount of energy consumed per tkm of renewable propane pipeline transport is based on GREET 2022 model, using crude oil pipelines as a proxy. Weighted average energy to transport 1 MJ over a distance of 1 km by pipeline was used to model the energy use. Electricity is responsible for 100% of the energy needed for pump operations. The average Canadian average grid was used to reflect the emissions due to the average electricity usage across Canada.

Fugitive emissions, emergency response emissions and venting emissions were excluded for renewable propane transport and only flaring emissions were included. The 2021 reference year data collected for 2023 Canada's National Inventory Report (NIR, 2023) is used to quantify flaring emissions from propane pipelines, using natural gas as a proxy.

This process is considered representative of pipeline transport of liquid renewable propane in Canada. However, some data was sourced from U.S. references. The processes can be used regardless of geographical location.

The main data sources used are listed below:

- GREET (2022). The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2022). Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89
- Government of Canada. (2023). National inventory report : greenhouse gas sources and sinks in Canada

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[35] Based on internal communication with Transport Canada (May 2023)

3.8.5 Predefined transport scenarios

When a user of the Model does not have information about the transportation distances and modes for the feedstock or the finished fuel, pre-defined transport scenarios are available to estimate the contribution of these life cycle stages. In some instances, the pre-defined scenarios are available for two options: “low-impact” and “high-impact” transport scenarios. Decision criteria for each option can be provided in the instructions of a specific program. Otherwise, it is at the discretion of the user to decide if a low- or high-impact scenario should be applied, based on information available in this chapter.

The Model contains three types of predefined transport scenarios: feedstock transport, fossil fuel distribution (i.e. natural gas and propane) and LCIF distribution (i.e. gaseous and liquid LCIFs).

In a predefined transport scenario, the distances and transport modes of the transported feedstock, fossil fuel or LCIF, are predetermined. The functional units of the three predefined transport scenario types are:

- Feedstock transport: 1 kg (dry-basis, where applicable) of feedstock transported to the fuel production plant (e.g. 1kg (dry-basis) of agricultural residue to a hydrogen plant)
- Fossil fuel transport: 1 MJ of gaseous fossil fuel (natural gas or propane) transported from the production plant to the end-user
- LCIF distribution:
    - 1 MJ of LCIF (gaseous) transported from the production plant to the end-user (via injection in a natural gas pipeline)
    - 1 MJ of LCIF (liquid) transported from the production plant to the delivery point (no specific transport mode assumed) (Leg 1)
    - 1 MJ of LCIF (liquid) transported from the delivery point to the end-user (via truck (diesel) transport) (Leg 2)

As mentioned in the generic transport section and as stated in **Chapter 2.3.1**, the manufacturing of fuel transport infrastructure (i.e., trucks, ships, and rail) was excluded from the Model. Also excluded are any on-site transport within the processing or conversion facility boundaries.

Modelling approach for predefined transportation scenarios

Each sub-section describes the modelling approach taken for that type of predefined transport, with the data sources used are provided in the following subsections.

Feedstock transport

Feedstock transport includes the transport of the feedstock from the source (i.e. where the feedstock is produced) to the production facility (including all intermediate steps).

The generic modes of transportation for the feedstock transport include: truck, rail and ship. The various transportation modes (e.g. truck, train or ship) included in the predefined feedstock transport scenarios are all based on conventional fossil fuels (e.g. truck transport is based on a diesel powered truck and not a biofuel powered truck). In the case of imported feedstocks, the Model also includes transport analysis to account for transport related emissions that occur outside of the Canadian boundaries (e.g. transoceanic shipping).

Predefined transport scenarios are presented on a “low-impact” and a “high-impact” base for each feedstock transport. Similar to the LCIF distribution, a “low-impact” scenario has been modelled to add 1 g CO_2e/MJ of fuel, whereas a “high-impact” scenario has been modelled to add 3 g CO_2e/MJ of fuel. The “low-impact” scenario only assumes truck transport, whereas the “high-impact” scenario assumes a combination of truck, rail and ship transport. The predefined distances for each feedstock transport scenario are based on the distance an amount of feedstock needed to produce 1 MJ of fuel has to be transported to increase the CI of the fuel by 1 or 3 g CO_2e, using the CI of the generic transport processes in the Model and a generic yield of fuel. Resulting transport distances (kg-km) are then rounded for simplicity.

Transport distances needed to determine emissions for each feedstock scenario are hence based on the following parameters:

- Feedstock amount at the production facility and co-product allocation at the production facility to produce 1 MJ of fuel
- Moisture content to adjust weight of feedstock amount (where applicable)
- Transport CIs (**Chapter 3.8.1**)

The main data sources used are listed below:

- Humbird, D., Davis, R., Tao, L., Hsu, D., Aden, A., Schoen, P., … Duedgeon, D. (2011). Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis. Golden, CO: National Renewable Energy Laboratory
- Natural Resources Canada. (2019). Confidential ethanol production data from ecoEnergy for Biofuels Complementary Environmental Performance Reports
- Chen, R., Qin, Z., Han, J., Wang, M., Taheripour, F., Tyner, W., Duffield, J. (2018). Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts
- Ramsden, T., Ruth, M., Diakov, V., Laffen, M., & Timbario, T. A. (2013). Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios
- Han, J., Elgowainy, A., Cai, H., & Wang, M. Q. (2013a). Life cycle analysis of bio-based aviation fuels. Bioresource Technology 150, 447-456
- Chu, P. L. (2014). Environmental and Financial Performance of Aviation Biofuels
- (S&T)2 Consultants Inc. (2011). The Addition of Pyrolysis Oil Pathways to GHGenius
- CIRAIG. (2019). Technical Report: Data to Inform Life Cycle Assessment of Key Canadian Renewable Natural Gas

Fossil fuel distribution

The predefined scenarios for fossil fuel distribution include the transport of the gaseous fossil fuel (i.e. natural gas and propane) from the production facility to the end-user.

For natural gas distribution, the predefined transport scenario has been developed based on the assumption that natural gas is transported by pipeline over a distance of 2560 km. This distance corresponds to an average of the distances traveled by natural gas in each province that is weighted based on natural gas consumption within each province using 2016 data from the NEB. The distances in each province were assumed to be the distance between the natural gas starting point in each producing region and the major city located in that gas producing region. Transport data on fugitive, venting and flaring emissions from natural gas pipelines is based on actual data from CEPEI (ORTECH 2018).

For propane distribution, the predefined transport scenario has been developed based on the assumption that the propane is transported by pipeline over a distance of 591 km to a regional hub and then the downstream distribution to end-users is assumed to be by truck over a distance of 296 km.

The predefined pipeline distance for propane was calculated with a weighted average pipeline distance using the total lengths of pipelines used for propane distribution based on data from Enbridge and the fraction of domestic propane that is transported between Western Canada (represented by Fort Saskatchewan) and Eastern Canada (represented by Sarnia, Ontario). That fraction was estimated by ECCC using data on domestic propane demand and propane production from the Conference Board of Canada. The truck transport distance represents an average of fossil fuel transportation distances in Western and Eastern Canada which was weighted based on the domestic propane demand in Canada. The transport distances in Western and Eastern Canada were estimated based on ECCC expert judgment.

The main data sources used are listed below:

- NEB. (2017b). Canadian Marketable Natural Gas Production - Open Government Portal
- National Energy Board and Competition Bureau. (2014). Propane Market Review - Final Report.
- Enbridge Inc. Interactive Map
- The Conference Board of Canada. 2021. Canada’s Propane Supply Chain, Reliability and resilience
- Murillo, Carlos A., Ova Adagha, Len Coad, and Greg Sutherland. Fueled Up: An Updated Overview and Outlook of Canada’s Propane Market and Industry. Ottawa: Conference Board of Canada, December 2018
- ORTECH Environmental, 2018, Canadian Natural Gas Transmission and Distribution Companies 2016 Greenhouse Gas Inventory

LCIF distribution

LCIF distribution includes the life cycle stages that bridges fuel conversion and use by the end-users. This includes the transport from the production facility to a distribution facility or a delivery point and then to the end-users. The predefined scenarios for LCIF distribution include transport scenarios for gaseous and liquid LCIFs. All the predefined transport scenarios for the gaseous LCIFs (i.e. hydrogen, RNG and renewable propane) assume that the produced LCIF is injected into an existing natural gas pipeline. The predetermined distance for these scenarios is hence identical to the predefined distance of natural gas distribution (please refer to the previous subsection *Fossil fuel distribution*).The energy usage for the natural gas pipeline is based on the GREET model (please refer to subsection *Gas Pipeline*). The predefined transport scenario for RNG also includes non-combustion emissions to represent fugitive, venting, flaring and emergency response emissions from the LCIF transmission and distribution stages. These emissions are based on data from CEPEI (ORTECH Environmental 2018). The predefined transport scenario for renewable propane only includes flaring emissions.

Predefined transport scenarios of liquid LCIFs are further broken down into two legs; leg 1 represents the transport from the production plant to the delivery point and leg 2 represents the transport from the delivery point to the end-user.

The predefined transport scenarios of the liquid LCIFs for leg 1 are presented on a “low-impact” and a “high-impact” base for each fuel type. Similar to scenarios for feedstock transport, the “low impact” scenario has been modelled to add 1 g CO_2e/MJ of fuel, whereas the “high-impact” scenario has been modelled to add 3 g CO_2e/MJ of fuel.

For leg 2, the predefined transport scenarios do not include high-impact and low-impact scenarios for each liquid LCIF. Instead, a predefined scenario is included for each liquid LCIF based on the assumption that these are transported by truck (diesel powered) over a set distance of 290 km. This weighted average distance to deliver refined fuel to the end-users was estimated based on ECCC expert judgement.

The main data source used is listed below:

- Based on ECCC assumption and expert input

Chapter 4: Fuel Pathways

This chapter presents the approach taken for the modelling structure of the unit processes in the fuel pathways of the Model. Refer to the *Fuel LCA Model User Manual* for how to use the fuel pathways alongside the Data library. This includes fuel pathways, which are templates to model the entire life cycle of fuels, and configurable processes, which are templates to model individual activities related to a life cycle.

4.1 Fuel pathway structure

As mentioned in **Chapter 2.3**, the Model contains five main life cycle stages, starting with feedstock production and ending with fuel combustion. The fuel pathways have been designed to allow the modelling of all five life cycle stages but are structured differently than what would practically occur for a fuel life cycle. The general structure is shown in **Figure 14**.

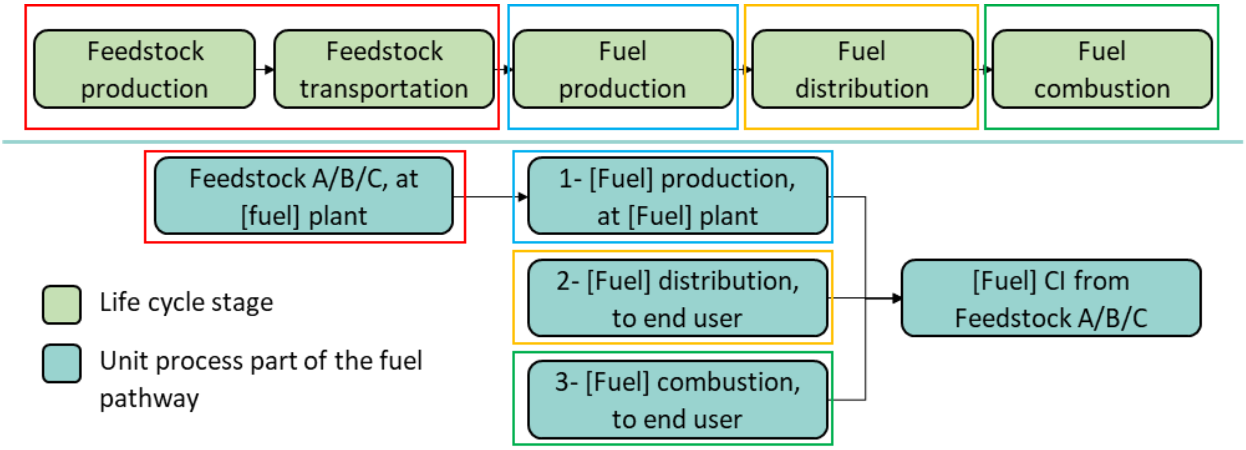

Figure 14: Top: five main life cycle stages. Bottom: general structure of fuel pathways in the Model Database

The structure of the fuel pathways was designed to represent different fuels and to account for different situations. The design allows for a high degree of customization to adapt itself to the need of different programs. For example, the fuel pathways include three feedstock production unit processes for the modelling of different feedstocks for a single fuel. Furthermore, each feedstock may have its own transportation needs, so the transportation step is grouped with feedstock production. The fuel production and fuel distribution life cycle stages are separate to allow for proper allocation at the fuel production stage, given that co-products may not all undergo the same distribution. The fuel combustion process allows for the input of the Data Library system processes that contain combustion emission factors. Finally, the "[Fuel] CI from Feedstock A/B/C" unit process combines the three previous processes to easily allow a user to calculate a CI without having to create complex links between other processes.

A new hydrogen pathway has been included in the Fuel pathways folder. This pathway has distinct characteristics compared to other fuel pathways, such as a cradle-to-gate (feedstock production to fuel production life cycle stages) scope and a functional unit expressed in terms of mass (kg of hydrogen) instead of MJ HHV. In addition, the pathway includes two modelling options: simplified and advanced. The simplified modelling approach is largely similar to the current approach used by other pathways (but excluding distribution and combustion). The advanced modelling approach allows users to break the production life cycle stage into more than one unit process. This option offers the possibility to apply energy or mass-based allocation to co-products generated by unit processes that are part of the production life cycle stage, allowing for a more representative modelling of the product system. Users can refer to instructions of programs for more information related to the use of this pathway.

The design of the fuel pathway dedicated to Fuel and Other Energy Sources for Vehicles (FOESV) is slightly different from the other fuel pathways. There is an additional life cycle stage between fuel distribution and fuel combustion: Fuelling station. Also, the first three life cycle stages are grouped under Fuel production. Finally, the distribution life cycle stage is broken into three unit processes: 2-Leg 1, 2-Treatment facility, and 2-Leg 2. The fuel pathway structure for FOESV is shown in **Figure 15**.

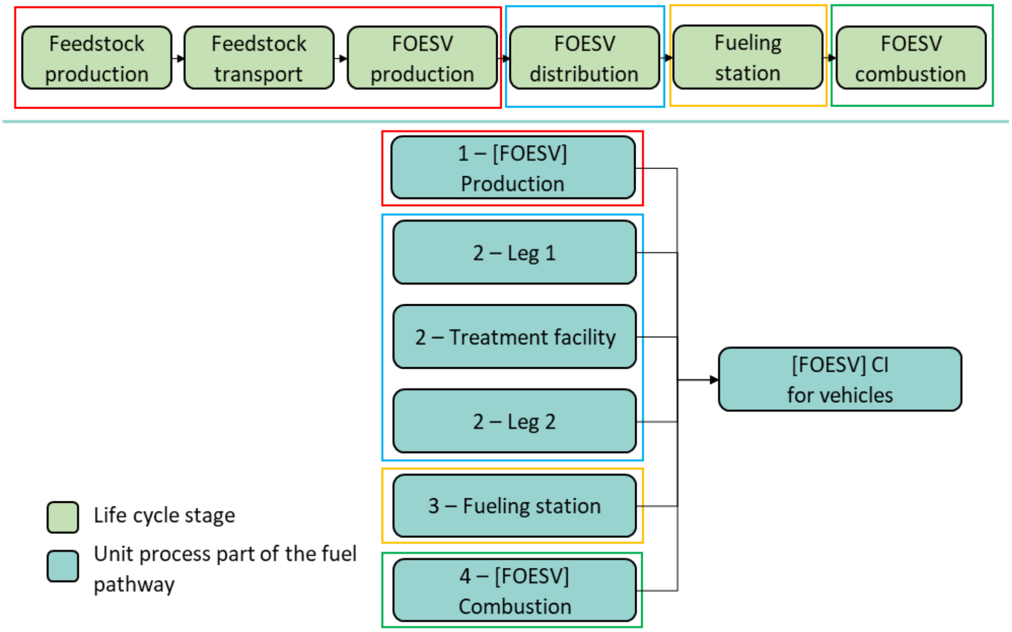

Figure 15: Top: six life cycle stages for FOESV. Bottom: structure of a Fuel pathway dedicated to FOESV in the Model Database

4.2 Configurable processes

The Model contains multiple configurable unit processes to provide templates that represent feedstock, electricity, and other scenarios. The processes are partially modelled but allow the use of specific inputs from the Data library. The modelling approaches for each type of configurable process included in the database are described in the following sub-sections.

4.2.1 Modelling approach for animal fats configurable processes

The animal fats configurable processes were modelled from the Canadian animal fat process available in the Data Library (**Chapter 3.5.1**). The LCI was calculated excluding electricity as well as local animal by-product transport inputs. The LCI results were then added to the output of the configurable processes, while an electricity dummy flow, an international ship transport, a train transport and local and international truck transport (25 tonnes and 45 tonnes payloads) flows were added as inputs. A default energy consumption of 0.1786 kWh is assigned to the dummy flow and a default trucking distance of

196.16 kg*km (representing the load-distance over the default trucking distance of 100 km) is assigned to the domestic 25 tonnes truck payload while the other flows are set at zero.

The user can replace the dummy flow with an electricity flow to represent the grid mix of their geographical location and add the calculated load-distance to all transport modes that are applicable. If a mode is not used, the user leaves it at zero.

All data sources for this configurable process are listed in **Chapter 3.5.1.**

4.2.2 Modelling approach for CCS configurable processes

The CCS configurable processes do not contain modelling. They are used to enter the net emission reductions from captured CO_2 at a fuel production plant and sent to permanent storage or used for an enhanced oil recovery project with permanent storage. This amount is set by the user or in accordance with the instructions of a program. The net reduction is calculated as the sum of emissions associated with CO_2 capture, transportation, injection and recycle stream minus the quantity of CO_2 permanently stored[36]. However, it is important to not double count emissions reductions: a negative fossil CO_2 value for the quantity permanently stored should only be considered in the calculation of net emissions reductions if the quantity of CO_2 captured has not been subtracted from the emissions of the fuel production process that would have occurred without CCS or if the captured CO_2 emissions from the fuel production process are biogenic.

The captured CO_2 is modelled as a waste flow, which can then be added as an output in a fuel production process.

4.2.3 Modelling approach for corn oil configurable processes

The corn oil configurable processes were modelled as a co-product of dry mill ethanol production from the fermentation of corn feedstock. The boundary of the corn oil production process begins with the corn production and ends with the production of corn oil at the bioethanol plant. **Figure 16** shows the processing steps modelled in the development of the corn oil configurable process. The functional unit is 1 kg of oil extracted at the bioethanol plant, prior to distribution.

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[36] The user can also add existing processes from the Data Library directly in these processes to model capture, transport and injection activities of captured CO_2.

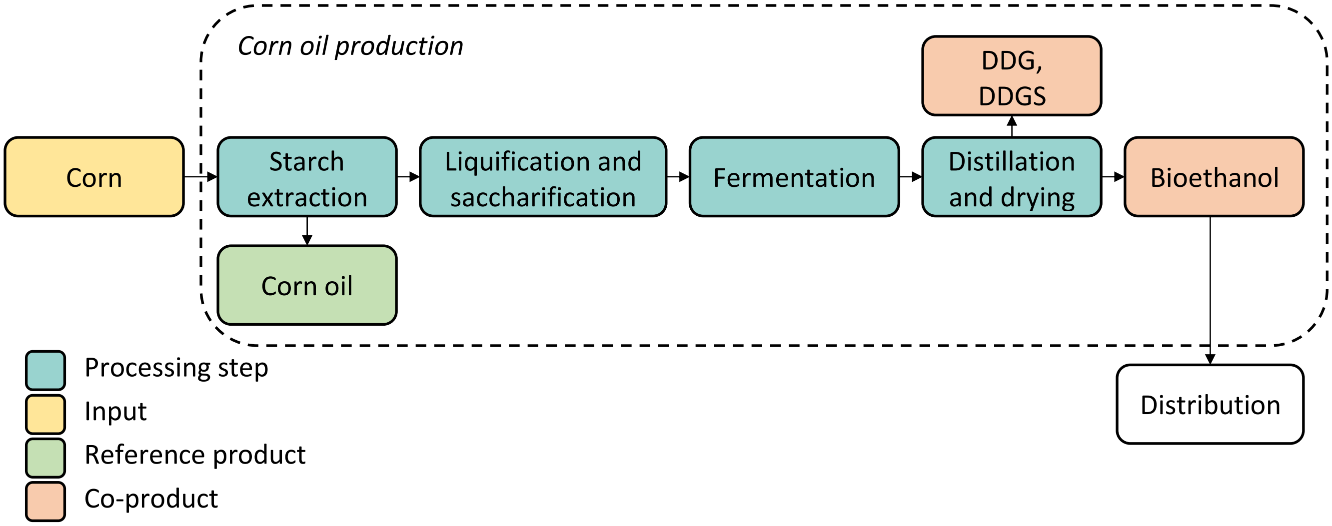

Figure 16: Processing overview for the production of corn oil in Canada and America

During the ethanol separation process, three main co-products are generated: corn ethanol, corn oil, and dried distillers grains with solubles. The allocation of burdens to the co-products is performed according to the energy content of the co-products.

The corn oil production processes were adapted from the corn ethanol dry milling pathway with corn oil extraction in GREET 2019.

The configurable processes were modelled by calculating the LCI of the corn oil production process, excluding the electricity and local corn transport inputs. The LCI results were then added to the output of the configurable processes, while an electricity dummy flow, an international ship transport, a train transport and local and international truck transport (25 tonnes and 45 tonnes payloads) flows were added as inputs. A default electricity consumption of 0.1855 kWh is assigned to the dummy flow and a default trucking distance of 254.72 kg*km (representing the load-distance over the default trucking distance of 100 km) is assigned to the domestic 25 tonnes truck payload while the other flows are set at zero.

The user can replace the dummy flow with an electricity flow to represent the grid mix of their geographical location and add the calculated load-distance to all transport modes that are applicable. If a mode is not used, the user leaves it at zero.

List of main data sources used for the modelling of the production of corn oil:

- CIRAIG. (2021). Technical report: Data to Inform Life Cycle Assessment of Canadian Imported Biofuels
- GREET (2019). The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. Argonne National Laboratory. (GREET 2019)

4.2.4 Modelling approach for grid electricity configurable processes

The grid electricity configurable processes do not contain additional modelling. They are used to create electricity grid mixes for regions that are not already covered in the Data Library. Any of the electricity production technologies in the inputs section of the unit process can be set by the user, with the total amount of electricity equalling 1 kWh.

4.2.5 Modelling approach for oil from oilseed configurable processes

The oil from oilseed configurable processes were modelled based on an average of vegetable oil production processes from canola oil, soybean oil, and camelina oil. Model users can use one of the configurable processes to model the oil production from oilseeds in a given region. Oilseed cultivation, and oil extraction were modelled in the development of the configurable processes.

Oilseed cultivation was modelled as described in **Chapter 3.5.2**, using the same design and data sources as corn, wheat, barley, and field peas.

Most of the LCI for camelina and soybeans were developed using the same data sources from the CRSC reports and the modelling approach remained the same ((S&T)^2 Consultants Inc. 2022f). Data gaps were filled in using data from the Government of Saskatchewan's Crop Planning Guide and Specialty Crop Reports (Agriculture 2018-2020 reports). The main data sources are listed at the bottom of this section.

The provincial data used for the three oilseed crops from the CRSC reports is shown in **Table 8**.

Table 8: Geographical scope of camelina, canola, and soybean oilseeds used to model the oil from oilseed configurable processes

Crop	**AB**	**BC**	**MB**	**NB**	**NL**	**NS**	**ON**	**PE**	**QC**	**SK**
Camelina	No	No	No	No	No	No	No	No	No	Yes
Canola	Yes	Yes	Yes	No	No	No	No	No	No	Yes
Soybean	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes

During the oil extraction process, a protein-rich meal is produced as a co-product. An overview of the processing steps for oil extraction from oilseeds is presented in **Figure 17**.

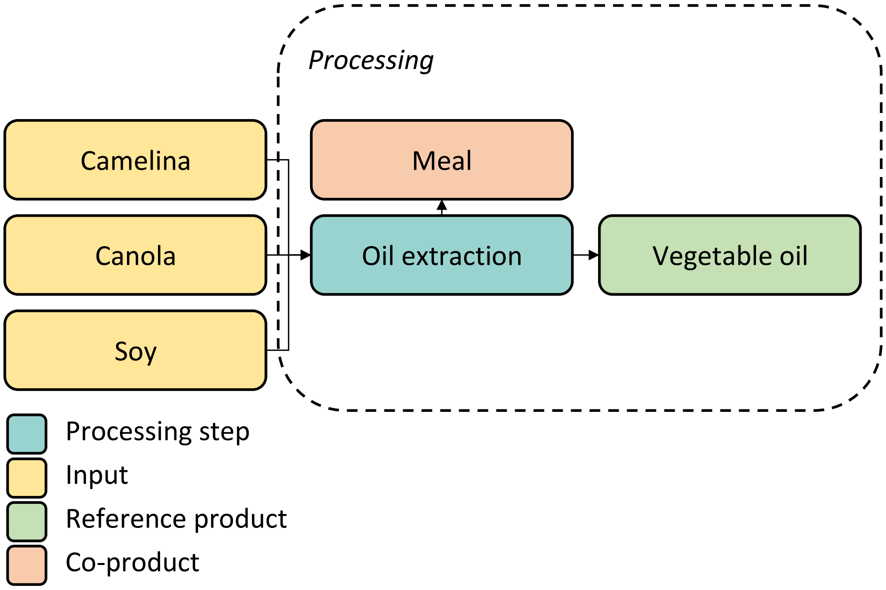

Figure 17: Processing overview for the extraction of vegetable oil feedstock from oilseeds

Oil extraction data was compiled from U.S and Canadian literature review for camelina oil (Shonnard 2010), canola oil((S&T)^{2} Consultants Inc. 2010) and soybean oil production (Chen 2018).

The allocation of burdens to the meal protein and oil in the oil extraction is performed according to the dry-mass content of the products.

For coherence among all types of oil extraction processes, the total thermal energy requirement for all oil extraction processes is assumed to be always supplied through the combustion of natural gas.

The configurable processes were modelled by calculating the LCI of the oilseed extraction process excluding the electricity as well as local oil seed transport inputs. The LCI results were then added to the output of the configurable processes, while an electricity dummy flow, an international ship transport, a train transport and local and international truck transport (25 tonnes and 45 tonnes payloads) flows were added as inputs. A default electricity consumption of 0.03334 kWh is assigned to the dummy flow and a default trucking distance of 111.15 kg*km (representing the load-distance over the default trucking distance of 100 km) is assigned to the domestic 25 tonnes truck payload while the other flows are set at zero.

The user can replace the dummy flow with an electricity flow to represent the grid mix of their geographical location and add the calculated load-distance to all transport modes that are applicable. If a mode is not used, the user leaves it at zero.

List of main data sources used for the modelling of oil extraction from oilseeds

Production:

- (S&T)^{2} Consultants Inc. (2010). Life cycle analysis of canola biodiesel. Winnipeg, MC: Canola Council of Canada. Retrieved from: Canola biofuels

- (S&T)^2 Consultants Inc. (2022a). Updated Carbon Footprint for Canadian Canola. Ottawa, ON: Canadian Roundtable on Sustainable Crops. Retrieved from: Canadian Grains Sustainability
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4.2.6 Modelling approach for oxygen configurable process

Processes have been modelled for a two-column cryogenic air separation plant where three compressors and one pump are used to isolate nitrogen and oxygen liquid flows (at 5 bar pressure). The electricity input for the three compressors and pump is based on the report *Energetic, exergetic and economic assessment of oxygen production from two columns cryogenic air separation unit* (2015).

After separation, the liquid oxygen flow is pressurized to a gaseous phase at 29.2 bar. The electricity input for the pressurization is based on the 2023 *Gate-to-Gate Carbon Intensity Hydrogen* study from National Research Council Canada (NRC).. This pressure is suitable for pipeline injection. Possible recompression and loss along pipeline are excluded.

As a conservative assumption, it is assumed that only oxygen is used, the nitrogen is considered as vented. Hence all impacts are allocated to oxygen output.

The user can replace the dummy flow for electricity with an electricity flow to represent the grid mix of their geographical location.

List of main data sources used for the modelling of oxygen:

- Armin Ebrahimi, Mousa Meratizaman, Hamed Akbarpour Reyhani, Omid Pourali, Majid Amidpour, *Energetic, exergetic and economic assessment of oxygen production from two columns cryogenic air separation unit,* 2015 DOI:10.1016
- National Research Council (NRC), *Gate-to-Gate Carbon Intensity Hydrogen* (2023). Internal report.

4.2.7 Modelling approach for yellow grease configurable processes

The yellow grease configurable processes were modelled from the Canadian yellow grease process available in the Data Library (**Chapter 3.5.1**). The LCI was calculated excluding electricity, as well as local raw UCO transport inputs. The LCI results were then added to the output of the configurable processes, while an electricity dummy flow, an international ship transport, a train transport and local and international truck transports (25 tonnes and 45 tonnes payloads) flows were added as inputs. A default electricity consumption of 0.069444 kWh is assigned to the dummy flow and a default trucking distance of 423.36 kg*km (representing the load-distance over the default trucking distance of 313.6 km) is assigned to the domestic 25 tonnes truck payload while the other flows are set at zero.

The user can replace the dummy flow with an electricity flow to represent the grid mix of their geographical location and add the calculated load-distance to all transport modes that are applicable. If a mode is not used, the user leaves it at zero.

All data sources for this configurable process are listed in **Chapter 3.5.6**.

Appendix A: Supplemental parameters for unit conversions

The Model uses several different unit types that are sometimes atypical from conventional units for data collection to allow for consistent LCA modelling. This section includes some common conversions that can be used with the Model.

Table 9: Supplemental feedstock conversion values

Feedstock category	Feedstock type	Density	Unit	Data source
Grains	Barley	48	wet lbs/bushel	US Grain Council. Converting Grain Units.
Grains	Corn	56	wet lbs/bushel	US Grain Council. Converting Grain Units.
Grains	Wheat (non-durum)	60	wet lbs/bushel	US Grain Council. Converting Grain Units.
Field peas	Field peas	60	wet lbs/bushel	US Grain Council. Converting Grain Units.
Vegetable Oils and animal fat	Animal fat	0.884	kg/L	GHGenius 5.01e (tab "Fuel Char"), based on density for tallow
Vegetable Oils and animal fat	Corn oil	0.915	kg/L	GHGenius 5.01e (tab "Fuel Char"), based on density for canola oil
Vegetable Oils and animal fat	Oil from oilseeds	0.915	kg/L	GHGenius 5.01e (tab "Fuel Char"), based on density for canola oil
Vegetable Oils and animal fat	Used cooking oil (UCO)	0.910	kg/L	GHGenius 5.01e (tab "Fuel Char"), based on density for used oil
Vegetable Oils and animal fat	Yellow grease	0.884	kg/L	GHGenius 5.01e (tab "Fuel Char")
Wood fibres	Wood chips, from unmerchantable logs	12.10	dry lbs/ft3	NRCAN's Solid Biofuels Bulletin No. 2 (Table 2).
Wood fibres	Wood pellets, from sawmill co-products	34.04	dry lbs/ft3	NRCAN's Solid Biofuels Bulletin No. 2 (Table 2).
Wood fibres	Wood pellets, from unmerchantable logs	34.04	dry lbs/ft3	NRCAN's Solid Biofuels Bulletin No. 2 (Table 2).

Table 10: Supplemental parameters for low carbon intensity fuels (LCIFs). For gaseous LCIFs, HHV and density are provided at a volume at standard conditions

LCIF	Parameter	Value	Data source
Bioethanol	HHV (MJ/kg)	29.67	Developed by ECCC based on references used for the NIR
Bioethanol	HHV (MJ/L)	23.42	Calculated

LCIF	Parameter	Value	Data source
Bioethanol	Density (kg/m^3)	789.30	Developed by ECCC based on references used for the NIR
Biodiesel	HHV (MJ/kg)	39.89	Developed by ECCC based on references used for the NIR
Biodiesel	HHV (MJ/L)	35.18	calculated
Biodiesel	Density (kg/m^3)	882.00	Developed by ECCC based on references used for the NIR
Biogas	HHV (MJ/L)	0.0186	Developed by ECCC
Hydrogenation derived renewable diesel (HDRD)	HHV (MJ/kg)	46.63	CA-GREET3.0 model ("Fuel_Specs" tab)
Hydrogenation derived renewable diesel (HDRD)	HHV (MJ/L)	34.92	calculated
Hydrogenation derived renewable diesel (HDRD)	Density (kg/m^3)	748.93	Calculated based on GREET 2018. Refer to "HHV GREET Calcs.xlsx"
Sustainable aviation fuel (SAF)	HHV (MJ/kg)	47.17	CA-GREET3.0 model ("JetFuel_WTP" tab)
Sustainable aviation fuel (SAF)	HHV (MJ/L)	36.40	calculated
Sustainable aviation fuel (SAF)	Density (kg/m^3)	771.60	Neste MY Sustainable Aviation Fuel Product Data Sheet
Renewable propane (gaseous)	HHV (MJ/kg)	51.34	Assumed to be the same as fossil propane
Renewable propane (gaseous)	HHV (MJ/L)	0.097	calculated
Renewable propane (gaseous)	Density (kg/m^3)	1.88	Assumed to be the same as fossil propane (gaseous)
Renewable propane (liquid)	HHV (MJ/kg)	51.34	Assumed to be the same as fossil propane
Renewable propane (liquid)	HHV (MJ/L)	25.31	calculated
Renewable propane (liquid)	Density (kg/m^3)	493.00	Assumed to be the same as fossil propane
Renewable natural gas (gaseous)	HHV (MJ/kg)	54.03	Assumed to be the same as gaseous natural gas
Renewable natural gas (gaseous)	HHV (MJ/L)	0.038	Assumed to be the same as gaseous natural gas
Renewable natural gas (gaseous)	Density (kg/m^3)	0.7105	Assumed to be the same as gaseous natural gas
Renewable natural gas (liquid)	HHV (MJ/kg)	55.21	Assumed to be the same as liquid natural gas
Renewable natural gas (liquid)	HHV (MJ/L)	23.64	Assumed to be the same as liquid natural gas
Renewable natural gas (liquid)	Density (kg/m^3)	428.20	Assumed to be the same as liquid natural gas
Hydrogen (gaseous)	HHV (MJ/kg)	141.92	CA-GREET3.0 model ("Fuel_Specs" tab)
Hydrogen (gaseous)	HHV (MJ/L)	0.013	calculated

LCIF	Parameter	Value	Data source
Hydrogen (gaseous)	Density (kg/m^3)	0.0899	Hydrogen Tools. Equation state calculator. Properties at 0 degrees C and 1 atm
Hydrogen (liquid)	HHV (MJ/kg)	141.80	CA-GREET3.0 model ("Fuel_Specs" tab)
Hydrogen (liquid)	HHV (MJ/L)	10.04	calculated
Hydrogen (liquid)	Density (kg/m^3)	70.8	CA-GREET3.0 model ("Fuel_Specs" tab)

Table 11: Supplemental parameters for LCIF co-products.

LCIF	Coproduct	Parameter	Value	Data source
Bioethanol	Animal feed (including DDG, WDG, DDGS, WDGS, gluten feed, gluten meal, germ)	HHV (MJ/kg dry basis)	21.75	R. V. Morey, D. L. Hatfield, R. Sears, D. Haak, D. G. Tiffany, & N. Kaliyan. (2009). Fuel properties of biomass feed streams at ethanol plants. *Applied Engineering in Agriculture*, 25(1), 57–64.
Bioethanol	Corn oil	HHV (MJ/kg dry basis)	36.55	EPA (2018). Emission Factors for Greenhouse Gas Inventories.
Bioethanol	Syrup, thin sillage	HHV (MJ/kg dry basis)	19.73	R. V. Morey, D. L. Hatfield, R. Sears, D. Haak, D. G. Tiffany, & N. Kaliyan. (2009). Fuel properties of biomass feed streams at ethanol plants. *Applied Engineering in Agriculture*, 25(1), 57–64.
Bioethanol	Lignin	HHV (MJ/kg dry basis)	25.60	GHGenius 5.01e (tab "Fuel Char")
Biodiesel	Distillation bottoms	HHV (MJ/kg dry basis)	42.21	GREET1_2022 ("Fuel_Specs" tab, cell D29)
Biodiesel	Free fatty acids	HHV (MJ/kg dry basis)	42.21	GREET1_2022 ("Fuel_Specs" tab, cell D29)
Biodiesel	Glycerin	HHV (MJ/kg dry basis)	18.10	GHGenius 5.01e (tab "Fuel Char")
Renewable hydrocarbon biofuels	Biochar	HHV (MJ/kg dry basis)	22.00	CA-GREET3.0 model ("Fuel_Specs" tab)

Table 12: Supplemental material input parameters

Chemical	Density (kg/m3)	Data Source
Methanol	794.1013539	CA-GREET3.0 model ("Fuel_Specs" tab)
Hydrogen (gaseous)	0.0899	Hydrogen Tools. Equation state calculator. Properties at 0 degrees C and 1 atm
Hydrogen (liquid)	70.8	CA-GREET3.0 model ("Fuel_Specs" tab)

Table 13: Supplemental parameters for other fuels

Type of fuel	Fuel	Parameter	Value	Data source
Fossil fuels	Aviation fuel	HHV (MJ/kg)	46.32	Calculated
Fossil fuels	Aviation fuel	HHV (MJ/L)	37.4	Based on value from the NIR
Fossil fuels	Aviation fuel	Density (kg/m^3)	807.4	Based on value from the NIR
Fossil fuels	Coal (bituminous)	HHV (MJ/kg)	28.37	Based on value from the NIR
Fossil fuels	Coal (lignite)	HHV (MJ/kg)	16.29	Based on value from the NIR
Fossil fuels	Coal (sub-bituminous)	HHV (MJ/kg)	18.44	Based on value from the NIR
Fossil fuels	Diesel	HHV (MJ/kg)	45.5	Developed by ECCC based on references used for the NIR
Fossil fuels	Diesel	HHV (MJ/L)	38.35	Calculated
Fossil fuels	Diesel	Density (kg/m^3)	842.9	Based on value from the NIR
Fossil fuels	Gasoline	HHV (MJ/kg)	45.8	Developed by ECCC based on references used for the NIR
Fossil fuels	Gasoline	HHV (MJ/L)	33.45	Calculated
Fossil fuels	Gasoline	Density (kg/m^3)	730.4	Based on value from the NIR
Fossil fuels	Heavy fuel oil	HHV (MJ/kg)	42.81	Calculated
Fossil fuels	Heavy fuel oil	HHV (MJ/L)	42.5	Based on value from the NIR
Fossil fuels	Heavy fuel oil	Density (kg/m^3)	992.8	Based on value from the NIR
Fossil fuels	Kerosene	HHV (MJ/kg)	46.67	Calculated
Fossil fuels	Kerosene	HHV (MJ/L)	37.68	Based on value from the NIR
Fossil fuels	Kerosene	Density (kg/m^3)	807.4	Based on value from the NIR
Fossil fuels	Light fuel oil	HHV (MJ/kg)	46.22	Calculated
Fossil fuels	Light fuel oil	HHV (MJ/L)	38.8	Based on value from the NIR
Fossil fuels	Light fuel oil	Density (kg/m^3)	839.5	Based on value from the NIR
Fossil fuels	Liquefied petroleum gas (LPG)	HHV (MJ/kg)	52.04	Calculated
Fossil fuels	Liquefied petroleum gas (LPG)	HHV (MJ/L)	26.41	Based on value from the NIR
Fossil fuels	Liquefied petroleum gas (LPG)	Density (kg/m^3)	507.5	Based on value from the NIR
Fossil fuels	Natural gas, gaseous	HHV (MJ/kg)	54.03	Calculated
Fossil fuels	Natural gas, gaseous	HHV (MJ/L)	0.038	CA-GREET3.0 model ("Fuel_Specs" tab)

Type of fuel	Fuel	Parameter	Value	Data source
Fossil fuels	Natural gas, gaseous	Density (kg/m^3)	0.7105	Enbridge. Learn about natural gas-Chemical composition of natural gas. Properties at standard conditions.
Fossil fuels	Natural gas, liquid	HHV (MJ/kg)	55.21	Calculated
Fossil fuels	Natural gas, liquid	HHV (MJ/L)	23.64	CA-GREET3.0 model ("Fuel_Specs" tab)
Fossil fuels	Natural gas, liquid	Density (kg/m^3)	428.2	CA-GREET3.0 model ("Fuel_Specs" tab)
Fossil fuels	Petcoke	HHV (MJ/kg)	36.24	Calculated
Fossil fuels	Petcoke	HHV (MJ/L)	43.46	Based on value from the NIR
Fossil fuels	Petcoke	Density (kg/m^3)	1199.3	Based on value from the NIR
Fossil fuels	Propane (gaseous)	HHV (MJ/kg)	51.34	Calculated
Fossil fuels	Propane (gaseous)	HHV (MJ/L)	0.097	Calculated
Fossil fuels	Propane (gaseous)	Density (kg/m^3)	1.8839	CA-GREET3.0 model ("Fuel_Specs" tab)
Fossil fuels	Propane (liquid)	HHV (MJ/kg)	51.34	Calculated
Fossil fuels	Propane (liquid)	HHV (MJ/L)	25.31	Based on value from the NIR
Fossil fuels	Propane (liquid)	Density (kg/m^3)	493.0	Based on value from the NIR
Fossil fuels	Stove oil	HHV (MJ/kg)	46.22	Assumed to be the same as light fuel oil
Fossil fuels	Stove oil	HHV (MJ/L)	38.8	Assumed to be the same as light fuel oil
Fossil fuels	Stove oil	Density (kg/m^3)	839.5	Assumed to be the same as light fuel oil
Other energy sources	Purchased steam	HHV (MJ/kg)	2.79	GHGenius 5.01e
Renewable fuels	Pellets, from agricultural residues	HHV (MJ/dry kg)	18.3	GREET 2018
Renewable fuels	Wood chips from sawmill co-products	HHV (MJ/wet kg)	10.5	Density values for wood fibres are based on parameters from NRCAN's "Solid Biofuels Bulletin No. 2" (see Table 2).
Renewable fuels	Wood pellets from sawmill co-products	HHV (MJ/wet kg)	19	Density values for wood fibres are based on parameters from NRCAN's "Solid Biofuels Bulletin No. 2" (see Table 2).