Fuel Life Cycle Assessment Model Methodology

January 2023

Environment and Climate Change Canada
Environnement et Changement climatique Canada

Canada

Cat. No.: En4-418/1-2023E-PDF
ISBN: 978-0-660-43852-8
EC22081

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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 *The 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).

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

The first 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 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.*

Ongoing development and maintenance activities will be 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
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* (hereafter referred to as the Model) to calculate the carbon intensity (CI) of fuels produced and used in Canada. The Model is publically available and is intended to inform and reduce the CI of Canadian fuels. 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 may also be used in the context of specific programs.

There are three main components of the Model:

1) **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) **Fuel LCA Model Methodology**: 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.
3) **Fuel LCA Model User Manual**: Provides information on general definitions and concepts related to LCA from the perspective of 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. Overall, the *Fuel LCA Model Methodology* describes the general assumptions, data sources and calculation procedures used in model development. 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 that apply for the database and the development of the 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 Fuel LCA Model Data Library.
- Chapter 4: Fuel Pathways: Describes the structure of the fuel pathways and the modelling approach of configurable processes included in the *Fuel LCA Model Database*.

This document is expected to be updated to reflect updates to the Model. For instructions about how to set up and use the Model, 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: Environmental management – Lifecycle assessment – Principles and Framework

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.

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**: inventory of input/output data with regard to the system being studied. Involves data collection.
- **Impact assessment**: provides additional information to help assess a product system's life cycle inventory (LCI) results so as to better understand their environmental significance.
- **Interpretation**: results are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

Figure 1 describes the relationships between the four phases. 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 with the life cycle approach results in a more complete picture when assessing the environmental impacts of a given process.

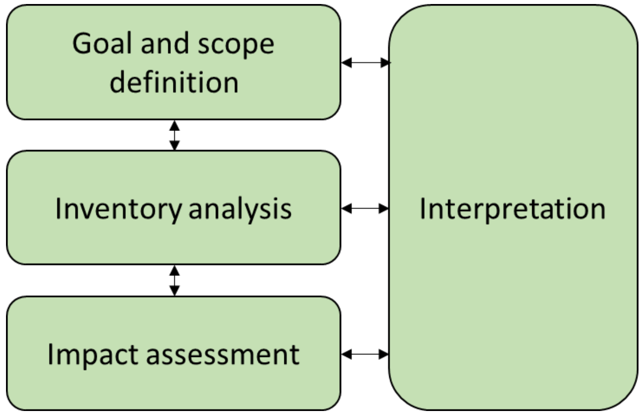


Figure 1: The four phases of an LCA study. Adapted from ISO 14040

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/disposal, allows for consideration of the environmental impacts of a full process 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 clear explanation of the methodology, complete documentation, and calculation procedures at the unit process level (see the next section 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]

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:

- Fuel pathway: Collection of unit processes (defined below), modelling parameters, and background data in the Model that allows the determination of the CI of a fuel from a particular feedstock.
- Data library: Collection of system processes that are used to support and model the unit processes in the fuel pathways.

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

- Life cycle stage: Collection of unit processes that model a specific part of a life cycle.
- Unit process: The smallest divisible process of a life cycle for which input and output data are quantified. Using flows, it transforms inputs into an output.
- System process: Aggregation of unit processes that models the LCI of a certain activity.
- Flow: Material or energy stream entering or leaving a unit process or system process.
    - Elementary flow: flow that is exchanged with the environment, e.g. GHGs
    - Intermediate flow: flow that is exchanged between unit processes.

Chapter 6 of the *Fuel LCA Model User Manual* provides detailed information about LCA concepts and definitions. The user manual also describes 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 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 CI values for LCIF pathways, fuel pathways, and configurable unit 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.

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 CI values or environmental impact 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. The functional unit for final fuels 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.

CIs are expressed in grams of carbon dioxide (CO_2) equivalents (g CO_2e) per unit of energy produced from combustion of the fuel in megajoules (MJ) on a HHV basis. 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 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**.

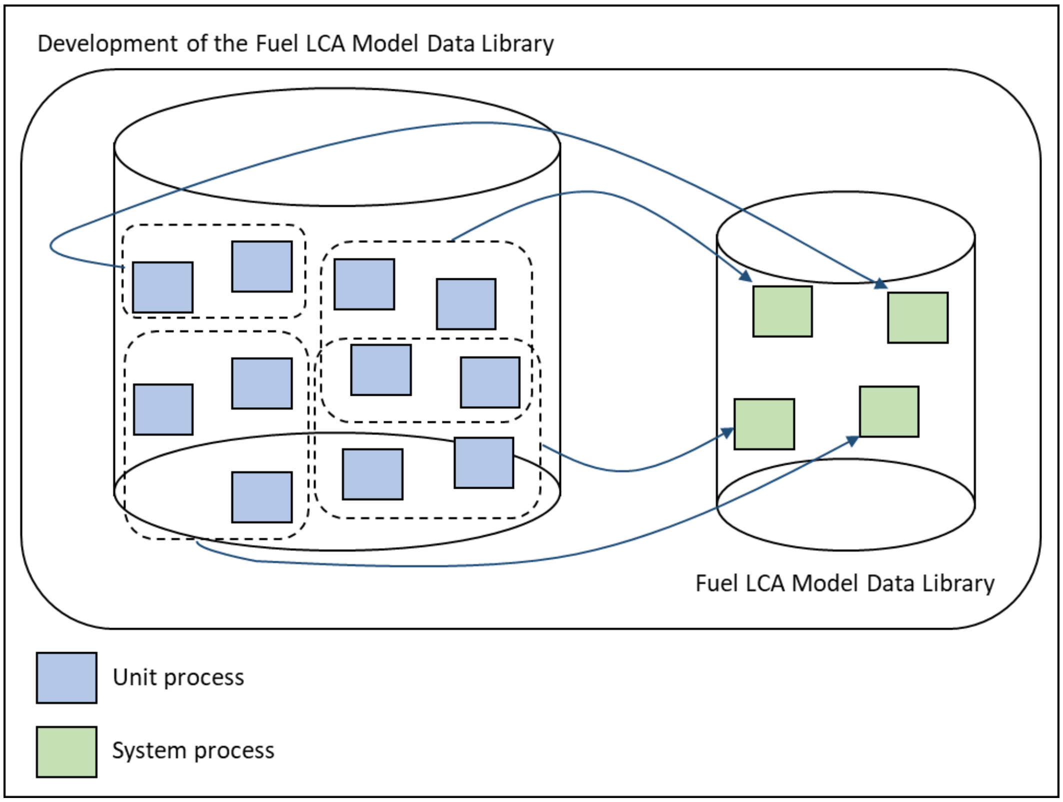


Figure 2: Visualization of the development of the *Fuel LCA Model Data Library*

2.2.3. Fuel pathways and configurable processes

The Model also 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 in **Table 1**.

Table 1: International system processes included in the *Fuel LCA Model Data Library*

Type of process	Geographical scope	Data documentation
Grain feedstock (sugar cane)	Brazilian states	Chapter 3.5.2
Grid electricity	American states	Chapter 3.3.2
Grid electricity	Brazilian national average	Chapter 3.3.2

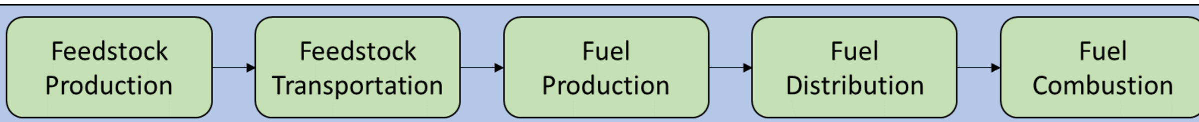
Furthermore, some of the Canadian processes were developed such that they can be applied as proxy for similar processes occurring in other regions. For example, natural gas production was modelled using Canadian data and sorghum was modelled using American data, but both of these processes can be used regardless of geographical location. System processes that are applicable beyond the Canadian context are identified as such in the data library, and are listed in **Table 2**.

Table 2: Processes in the Model data library that were developed for the Canadian context but are applicable to other regions

Type of process	Data documentation
Chemical inputs	Chapter 3.1
Combustion emission factors	Chapter 3.2
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
Technology-specific electricity	Chapter 3.3.2 (see section Modelling approach for electricity generation technologies)
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**.



- **Feedstock Production**: (or feedstock extraction) extraction of raw feedstock materials (e.g. corn cultivation, wood harvesting), including any upgrading or processing required prior to transport.
- **Feedstock Transportation**: transportation of raw and processed feedstock to the fuel producer.
- **Fuel Production**: (or fuel conversion) processes for converting the feedstock into fuels, including potential pre-processing of feedstocks, and post-processing and upgrading to final fuel product.
- **Fuel Distribution**: storage and handling of fuel, transport of finished fuel product to storage and to final user.
- **Fuel Combustion**: combustion of the final fuel product by the end user.

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

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.

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; and
- 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; and

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

2.4.1. Data collection for system processes in data library

The Model contains several different data sources for modelling the hundreds of system processes. **Table 3** presents the different data quality levels considered during data collection. 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.

Table 3: Definition of the data quality levels considered during the data collection process

Data quality level	Definition
High data quality	• Regionally specific and recent data (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 data from a larger region that include the region other study and no more old 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.

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:

[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).

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.

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]

CO_2 emissions from changes in two land management practices are taken into account in the modelling of all crops: changes in tillage practices and changes in summerfallow area. Carbon emissions from changes in the proportion of annual and perennial crops are not considered; indirect land use changes are excluded from 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).

[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. Available online at www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

2.8. Life cycle impact assessment method

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, the impact factors used are the IPCC's Fifth Assessment Report (AR5) global warming potential (GWP) for a 100-year time horizon.[4] 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 near-term climate forcers and climate-carbon cycle feedbacks are not considered in the LCIA method 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_2 equivalents per MJ of HHV energy. **Table 4** provides a summary of the GWP for the main GHGs. A complete list of GHGs with their associated GWP and uncertainty can be found in **Appendix A**.

In remaining consistent with the Government of Canada's policy on biogenic carbon, as shown in Canada's NIR (2018), the GWP for uptake of carbon during the biomass growth and emissions of biogenic carbon from combustion of low carbon fuels are assumed to be zero. 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.

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 4. Select characterization factors for calculating carbon intensities using IPCC AR5 GWP 100

Greenhouse gas	GWP 100-year
CO_2	1
CO_2 (biogenic)	0
CO_2 (land use change)	1
CH_4 (fossil)	30
CH_4 (biogenic)	28
N_2O	265
Sulfur hexafluoride	23,500

[4] 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.

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 publically 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 include notably enzymes, acids and catalysts. The CI for each of these chemicals is based on the 2018 *Greenhouse gases, Regulated Emissions, and Energy use in Technologies* (GREET) model life cycle emission factors. 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. The following chemicals are included in the Model (**Table 5**). Hydrogen is also included as a chemical input and is documented in **Chapter 3.1.3**. The functional unit for each chemical is 1 kg.

Table 5: Chemicals available in the Model data library

Included chemicals in the Model data library		
Acetic acid	Alpha amylase	Ammonia
Ammonium sulfate	CaO (lime)	Calcium carbonate
Cellulase protein	Cellulase	Citric acid
Corn steep liquor	Diammonium phosphate	Gluco amylase
Glucose	Hexane (n-hexane)	Hydrochloric acid
Methanol	Nitrogen gas	Phosphoric acid
Potassium hydroxide	Sodium hydroxide	Sodium methoxide
Sulfuric acid	Urea	Yeast extract
Yeast		

Geographical scope for chemicals

There is a lack of Canadian-specific LCI data for these chemicals. 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 chemicals

No allocation was performed for chemicals modelling.

Data sources for chemicals

Emission factors for chemicals were taken from the GREET 2018 model (**Table 6**).

Table 6: Main data source for the modelling of agrochemicals in the Model

Data type	Data source
Other chemicals, emissions values	Argonne National Lab. (2018). GREET.

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 in **Table 7**.

Table 7: List of main data sources used for the modelling of agrochemicals in the Model

Data type	Data source
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 (**Chapter 4:**). 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 main processing steps involved in the conversion of natural gas into hydrogen. 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.

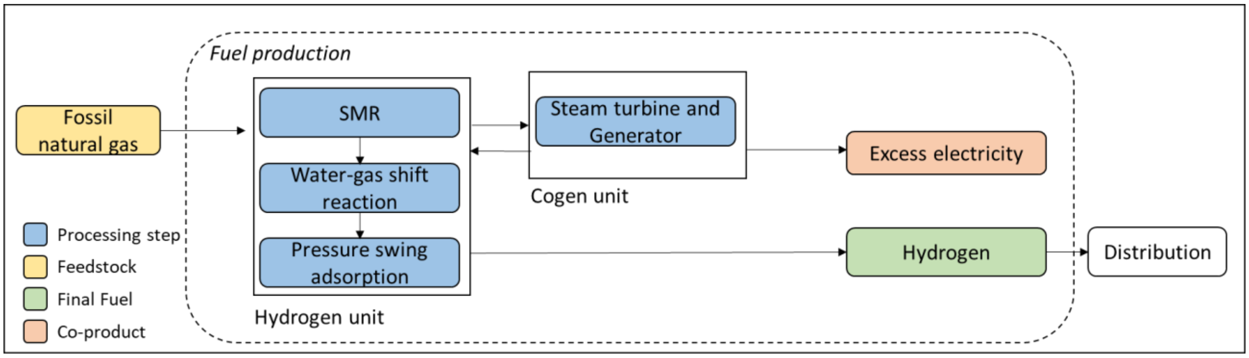


Figure 4: Main processing steps involved in the production of hydrogen from SMR

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 3.3.2** 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 Nm3/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. **Table 8** lists the main data sources used in modelling the conversion of hydrogen from natural gas.

Table 8: List of main data sources used for the modelling of hydrogen conversion from natural gas in the Model.

Data type	Data source
Natural gas conversion	IEAGHG. (2017). *Techno-Economic Evaluation of SMR Based Standalone (Merchant) Plant with CCS.* 2017/02, February. 2017. Retrieved from https://ieaghg.org/component/content/article/49-publications/technical-reports/784-2017-02-smr-based-h2-plant-with-ccs.
	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.* Retrieved from https://www.nrel.gov/docs/fy14osti/60528.pdf
	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. Each predefined chemical mix was calculated by modelling the emissions of the respective fuel and then identifying the specific contributions of chemical inputs. 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

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. Bioethanol produced from corn was used as the basis for chemical use modelling, and included modelling for starch extraction, liquefaction and saccarification, fermentation, and distillation and drying. The chemicals considered were: 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**. The LCI results were then used to create the predefined chemical mix for conventional bioethanol.

Geographical scope for predefined chemical mix for conventional bioethanol

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

The allocation of the LCI of the bioethanol and co-products is based on energy content.

Data sources for predefined chemical mix for conventional bioethanol

Detailed provincial and anonymized LCI data for Canadian grain bioethanol have been compiled by NRCan as part of NRCan's ecoENERGY for Biofuels Program. The data is aggregated from information provided in the CEPR from 2012 to 2015 years of production. A summary of the main data sources used for modelling bioethanol conversion is presented in **Table 9**.

Table 9: List of main data sources used for the modelling of predefined chemical mix for conventional bioethanol production

Data type	Data source
Crop volumes produced and used nationally	Littlejohns, J., Rehmann, L., Murdy, R., Oo, A., & Neill, S. (2018, 2018). Current state and future prospects for liquid biofuels in Canada. *Biofuel Research Journal, 5*(1), 759-779.
Regional bioethanol production	Natural Resources Canada. (2019). *ecoENERGY for Biofuels Program*. Retrieved from https://www.nrcan.gc.ca/energy/alternative-fuels/biofuels/12358 Natural Resources Canada. (2019). *Confidential ethanol production data from ecoEnergy for Biofuels Complementary Environmental Performance Reports.*

Modelling approach for predefined chemical mix for cellulosic bioethanol

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

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

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

The data used to model the production of cellulosic bioethanol 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. **Table 10** lists the main data sources used in modelling the cellulosic bioethanol conversion processes.

Table 10: List of main data sources used for the modelling of predefined chemical mix for cellulosic bioethanol production

Data type	Data source
Wheat straw processing steps	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: https://greet.es.anl.gov/publication-wte-2016 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.
Corn stover processing steps	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: https://greet.es.anl.gov/publication-wte-2016

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 for biodiesel production was determined based on data on biodiesel production from three different feedstocks and production processes, which are summarized in **Table 11**.

Table 11: List of biodiesel feedstocks, conversion processes, and chemical inputs used to model the predefined chemical mix for biodiesel

Feedstock	Conversion process	Chemical inputs modelled
Canola oil	Oil extraction, transesterification, refining	Potassium hydroxide, sodium methoxide, sulfuric acid
Animal fats	Rendering/purification, high free fatty acid conversion, transesterification/refining	Hydrochloric acid, nitrogen, sodium methoxide, potassium hydroxide, citric acid, phosphoric acid, sodium hydroxide, sulfuric acid
Used cooking oil (UCO)	Purification, free fatty acid conversion, transesterification/refining	Hydrochloric acid, sodium methoxide, nitrogen, phosphoric acid, sodium hydroxide, sulfuric acid

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 (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 2011-2015, provided by the CEPR. The emission factor for the predefined chemical mix was determined by calculating the impacts of the chemicals mentioned in the table above and creating an average based on the three production methods. Methanol was not included in the predefined chemical mix so that it can be modelled by the user.

Geographical scope for predefined chemical mix for biodiesel

The biodiesel production process from canola oil was modelled based on Canadian production data from the CEPR that have been compiled by NRCan as part of NRCan's ecoENERGY for Biofuels Program. The CEPR data was compiled to model a single national average approach for biodiesel conversion from oilseeds.

The biodiesel production process from beef tallow was modelled based on U.S. data from the GREET model and a survey performed by the American National Biodiesel Board. The data was compiled to model a single national average approach for beef tallow conversion.

The biodiesel production process from UCO was modelled based on Canadian and U.S. data from the GHGenius and GREET models, and a survey performed by the American National Biodiesel Board. The data was compiled to model a single national average for UCO conversion to biodiesel.

For all three pathways modelled it is assumed that the conversion process is the same across provinces. The resulting chemical mix process is intended to be used regardless of geographical location.

Allocation for predefined chemical mix for biodiesel

The allocation of burdens for the chemicals and other inputs for the biodiesel production is based on energy content of the product and co-products.

Data sources for predefined chemical mix for biodiesel

The data sources used for biodiesel production modelling from the three production methods is listed in **Table 12**.

Table 12: List of main data sources used for the modelling of predefined chemical mix for biodiesel production

Data type	Data source
Biodiesel from canola oil	Miller, P., & Kumar, A. (2013). Development of emission parameters and net energy ratio for renewable diesel from Canola and Camelina. *Energy, 58*, 426-437. Littlejohns, J., Rehmann, L., Murdy, R., Oo, A., & Neill, S. (2018, 2018). Current state and future prospects for liquid biofuels in Canada. *Biofuel Research Journal, 5*(1), 759-779. Natural Resources Canada. (2019). *Confidential biodiesel production data from ecoEnergy for Biofuels Complementary Environmental Performance Reports.* Natural Resources Canada. (2019). *ecoENERGY for Biofuels Program*. Retrieved from https://www.nrcan.gc.ca/energy/alternative-fuels/biofuels/12358
Biodiesel from 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.
Biodiesel from UCO	(S&T)[2] Consultants Inc. (2013). GHGenius Model 4.03 Volume 2 Data and Data Sources. Ottawa, ON: Natural Resources Canada. California Environmental Protection Agency. (2009). Detailed California-GREET Pathway for Biodiesel Produced in California from Used Cooking Oil 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

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

Table 13 lists 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 in **Table 13**, 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.

Table 13: Modelling approach and main data sources used for the modelling of fuel combustion included in the Model

Fuel	Modelling approach	Data sources
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.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715
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 CH_4 associated with methanol are neglected).	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715
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.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715
Hydrogen	As hydrogen combustion does not release GHGs, there is 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.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715
Propane	Emission factors for propane combustion from the NIR are used.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715
Renewable Diesel	Emission factors for fossil-based diesel combustion from the NIR are used as a proxy.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715
Renewable Gasoline	Emission factors for fossil-based gasoline combustion from the NIR are used as a proxy.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715

Renewable Naphtha	Emission factors for fossil-based kerosene combustion from the NIR are used as a proxy.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715
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.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715
Renewable Propane	Emission factors for fossil-based propane combustion from the NIR are used as a proxy.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/documents/65715
Sustainable Aviation Fuel	Emission factors for fossil-based aviation turbo fuel combustion from the NIR are used as a proxy.	Government of Canada. (2018). *National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from https://unfccc.int/document/65715

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 CI values for Canada, the U.S. and Brazil
- CI values for displaced electricity production associated with excess electricity exported to the grid
- Technology-specific CI values for electricity generation (e.g. "hydropower, reservoir")

Grid mixes

Table 14 shows the available grid mix CIs for Canada, the U.S., and Brazil.

Table 14: Regions covered in the data library for grid mix CIs

Country	Regions covered in the data library for grid mix CI values
Canada	• Canadian provinces and territories • Canadian average
United States of America	• U.S. states • U.S. average
Brazil	• Brazil average

The grid mix CIs for Canada and the U.S. only account for production within the region boundaries (province, territory or state) specific to each dataset. More specifically, the CI values include 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.

Inter-provincial (or inter-sate) and international trade are not included in the datasets. Biogenic carbon emissions and infrastructures related to electricity generation are also excluded.

The Brazilian grid mix CI was created by scaling the Canadian technology-specific system processes for electricity generation (refer to subsection *Electricity generation technologies* below) with the fraction of electricity produced in the region from each technology.

Excess electricity exported to the grid

The datasets for displaced electricity production associated with excess electricity exported to the grid have been developed for the regions specified in **Table 14** for Canada and the U.S. only. The excess electricity datasets were calculated using the same data and calculation approach as the grid mixes (see subsection *Modelling approach for grid mixes* below). However, because the amount of electricity exported to the grid is based on the quantity produced, the datasets for excess electricity do not include transportation and distribution to end-users and therefore exclude electricity losses and SF_6 emissions in transmission and distribution.

Electricity generation technologies

The data library includes several technology-specific processes for electricity generation (e.g. "hydropower, reservoir"), applicable across Canada. These are listed in **Table 15**. The datasets account for the direct emissions of electricity generation, as well as the upstream impacts of inputs to power generation, when relevant.

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.

Table 15: Onsite and offsite electricity generation technologies

Technology	**Onsite & offsite generation**
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	✓

3.3.2. Modelling approach for electricity

This section presents the modelling approach and assumptions for each category of electricity processes found in the data library.

Modelling approach for grid mixes

The functional unit for electricity grid mix processes is 1 kWh of electricity produced and distributed from the grid.

Canadian grid mixes

2018 provincial and national direct emissions for the grid from the NIR were used to model the provincial and national grid processes. The report presents annual data on electricity generation 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.

The main source of information for the grid mix composition is also found in the NIR. Because some of the fuels used for electricity generation and listed in the NIR are aggregated, additional data sources were used to identify the specific fuels used to generate electricity, as summarized in **Table 16**.

Table 16: List of main data sources used to disaggregate list of fuels in the NIR

Aggregated fuels listed in the NIR	Fuels covered	Data source
Coal	Lignite coal Bituminous coal Sub-bituminous coal	Statistics Canada Table 25-10-0019-01: "Electricity from fuels, annual generation by electric utility thermal plants". Available at: https://doi.org/10.25318/2510001901-eng
Other fuels[5]	Diesel Light Fuel Oil Heavy Fuel Oil	Statistics Canada Table 25-10-0028-01: "Electricity generated from fossil fuels, annual". Available at: https://doi.org/10.25318/2510002801-eng

Reservoir emissions are added to the grid mix emissions following the approach described in the subsection *Modelling approach for electricity generation technologies* below. The fraction of hydroelectricity in grid mixes is directly provided by the NIR. The fraction of hydroelectricity that is from reservoirs is based on factors derived 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 (see subsection *Modelling approach for electricity generation technologies* below for more information on CAFE3).

Fuel amounts 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. Heat rates for power plants consuming fossil fuels[6] are determined using Statistics Canada 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.

American grid mixes

The principal data source is eGrid (2018 data) which provides data for emissions, plant-level fuel consumption and quantity of electricity generated. The direct emissions per state are taken directly from the eGrid. These were divided by loss factors, defined at the North American Electric Reliability

[5] Biomass was excluded from the grid mix calculations

[6] For nuclear power plants, the heat rate is taken directly from the CAFE3 model.

Corporation (NERC) region level provided in eGrid. **Table 17** summarizes the main assumptions about the calculated heat rate values (in MJ of fuel per kWh of electricity output) for coal and oil.

Table 17: Description of methodology used to calculate heat rates

Fuel	Methodology for calculation of heat rates
Coal	• State-specific heat rate values (in MJ/kWh) were calculated. • Four additional coal types 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.

Reservoir emissions are estimated using world average emission factors from (Hertwitch, 2013) [7]. The total SF_6 emissions attributable to the power sector were taken from EPA'S *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019* (Table 2-11) for the year 2018.

Brazilian grid mix

A Brazilian grid mix was created by scaling the Canadian technology-specific electricity generation system processes (refer to subsection *Modelling approach for electricity generation technologies* below) with the fraction of electricity produced in the region from each technology according to 2018 data for Brazil from the International Energy Agency[8].

Modelling approach for excess electricity exported to the grid

Excess electricity produced from a LCIF production process and exported to the grid is assumed to displace the generation of electricity from other generators on the grid. A set of system processes representing the generation of electricity that is displaced is included in the data library in the "Displaced Grid Electricity" folder.

A cap of 345.4 g CO_2e/kWh was set on the CI values for excess electricity (i.e. excess electricity cannot displace more than 345.4 g CO_2e/kWh). This cap 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

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[7] Hertwich, Edgar G. 2013. "Addressing Biogenic Greenhouse Gas Emissions from Hydropower in LCA." Environmental Science & Technology 47 (17): 9604–11. https://doi.org/10.1021/es401820p.

[8] International Energy Agency. 2021. "Brazil Country Profile", available at: https://www.iea.org/countries/brazil

production based on the natural gas datasets from the Fuel LCA Model. The functional unit for excess electricity processes is 1 kWh electricity produced for the grid.

Modelling approach for electricity generation technologies

Direct emissions from electricity generation and fuel consumption inputs were calculated using the CAFE3 tool, 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.

While CAFE3 calculates CI values for fuels used in electricity generation, these were replaced, for greater coherence with the rest of the model, with the CI values of fuels in the Fuel LCA 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)[9]. 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).

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 offsite and delivered to the user.

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 CO2e 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**.

[9] 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. https://doi.org/10.1016/j.rser.2020.110433.

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 many feedstock processes used in LCIF production pathways. The data library "Feedstocks" folder has six main categories of feedstock that can be used in LCIF production: animal fats, crops (field peas, grains, and sugar cane), residues, waste, wood fibre, and yellow grease.

Other types of processes can be used for the modelling of feedstock. For example, hydrogen can use natural gas as a feedstock; 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**.

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.

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. 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. 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**.

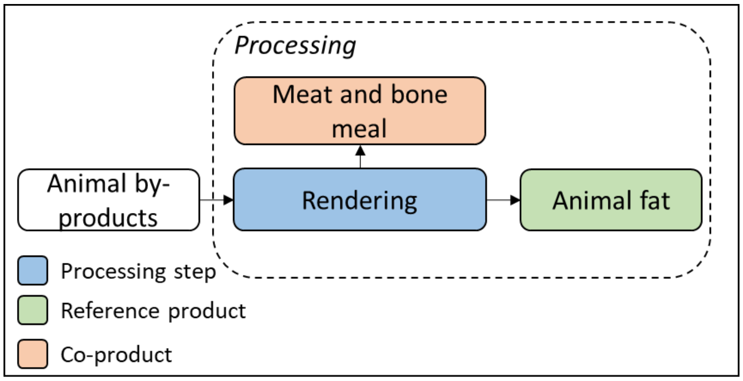


Figure 5: Main processing steps involved in the rendering of animal by-products into animal fat

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 the dry mass content of the products.

Data sources for rendering animal by-products into animal fat

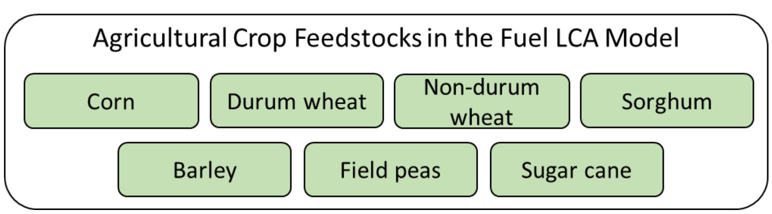
Table 18 lists the main data source used to model the production of animal fat. Beef tallow was used as a proxy for animal fats.

Table 18: List of main data sources used for modelling beef tallow production from animal by-products

Data type	Data source
Animal fat rendering	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:



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, while the second section presents the modelling for sorghum and sugar cane. The modelling approach is similar between the two groups of crops. For each of these feedstocks, the reference product 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 2017 LCA studies for major crops from the CRSC.

Each crop was modelled using eight production processes: tillage, seeding, irrigation[10], 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.

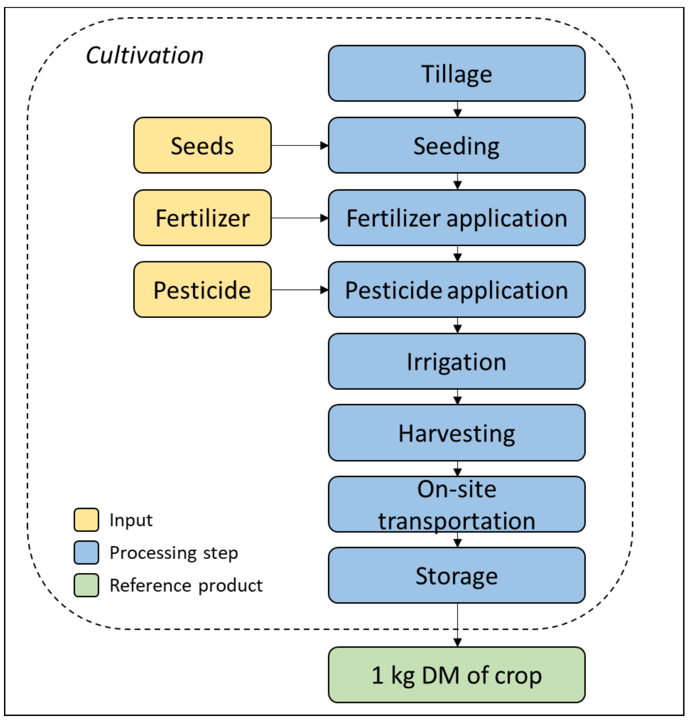


Figure 6: Cultivation overview for agricultural feedstocks, which represents the feedstock production life cycle stage.

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.

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

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

emission factors from the CRSC reports which take into account tillage type, irrigation practices, and topography.

In accordance with the approach in the NIR (2018), carbon emissions associated with SOC changes in Canada are included for the two following land management practices[11]:

- Changes in area of summerfallow
- 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 2014.

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 concerns raised related to differences in interprovincial CI and the application of Canadian Soil SOC values to U.S. crops[12]. The provincial datasets were modelled based on a Canadian average fertilizer mix as opposed to distinct provincial fertilizer mixes.

Regarding the exclusion of organic fertilizers such as manure, the Model uses the default approach from the Livestock Environmental Assessment and Performance guidelines[13] 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 the provincial datasets was then calculated for each crop using 2018/2020 average production data

[11] The pre-published version of the Model also included carbon emissions from changes in the proportion of annual and perennial crops. These emissions were excluded in the published version of the Model.

[12] More information is available in the Fuel-LCA-Model-Crops-VegetableOil-Update-Readme, published on the ECCC data catalogue on May 5, 2022.

[13] FAO. 2016. Livestock Environmental Assessment and Performance (LEAP) Partnership. http://www.fao.org/partnerships/leap/overview/goals-and-objectives/en/

from Statistics Canada. **Table 19** indicates which regions were included in the CI calculations for each crop.

Table 19: 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	✓	✓	✓	✓		✓	✓	✓	✓	✓
Corn			✓	✓		✓	✓	✓	✓	
Wheat (Durum)	✓									✓
Wheat (non Durum)	✓	✓	✓	✓		✓	✓	✓	✓	✓
Field Peas	✓	✓	✓							✓

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.

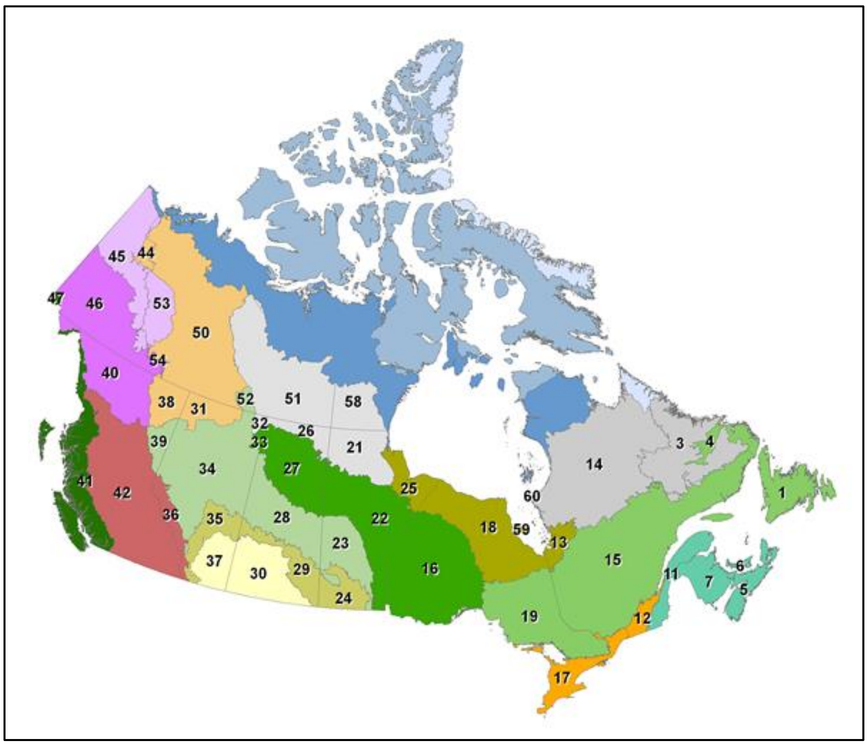


Figure 7: RUs in Canada[14]

[14] Natural Resources Canada. *Spatial Framework*. See https://www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/carbon-accounting/spatial-framework/13117

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 corn, wheat, barley and field peas were the main sources of data for compiling these LCI. The CRSC studies represent the current best available source of Canadian field crop LCI data.

The CRSC reports detail carbon footprints of corn, 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 GREET 2018 Model was used in determining their values. **Table 20** details the main data sources to model agricultural crop feedstocks.

Table 20: List of main data sources for the modelling of agricultural feedstock

Data type	Data source
Yield Seeding rates Fertilizer/pesticide rates Energy use N_2O emissions CO_2 emissions from SOC	Crop-specific CRSC reports on corn, wheat, durum wheat, barley and field peas: (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. (S&T)2 Consultants. (2017). *Carbon Footprint For Canadian Durum Wheat.* Winnipeg, MB: Canadian Roundtable on Sustainable Crops. (S&T)2 Consultants. (2017). *Carbon Footprint For Canadian Barley.* Winnipeg, MB: Canadian Roundtable on Sustainable Crops. (S&T)2 Consultants. (2017). *Carbon Footprint For Canadian Field Peas.* Winnipeg, MB: Canadian Roundtable on Sustainable Crops. (S&T)2 Consultants Inc. (2017c). *Carbon Footprints for Major Canadian Grains Methodology Report.* Winnipeg, MB: Canadian Roundtable on Sustainable Crops.
2018/2020 average production data	Statistics Canada. Table 32-10-0359-01 Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. Available at: https://doi.org/10.25318/3210035901-eng

Modelling approach for sorghum and sugar cane

The datasets for sorghum and sugar cane were generated based on a report developed for ECCC by consultancy firm, Quantis. As with the modelling of the other crops, the boundaries of the sorghum and sugar cane datasets considered 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[15].

The two crops were modelled using the same eight production processes as the other crops included in the Data Library: tillage, seeding, irrigation[16], 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[17] as implemented by the Cool Farm Tool[18].

As with the other crops, 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 and sugar cane followed the same scope as the 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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[15] Reinhard J., Bengoa X. & Liernur A. (2021): geoFootprint, Technical Documentation. Version 1, February 2021. Quantis, Lausanne, Switzerland. https://geofootprint.com/about/faq/

[16] 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.

[17] Bouwman AF, Boumans LJM, Batjes NH (2002) Modeling global annual N2O and NO emissions from fertilized fields. Glob Biogeochem Cycles 16:28–29. https://doi.org/10.1029/2001GB001812

[18] 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 and sugar cane

LCI data for sorghum and sugar cane was generated by the geoFootprint tool. The LCI for sorghum was based on data from the U.S., while the LCI for sugar cane was based on data from Brazil. The energy and material inputs (e.g. fertilizers, pesticide, diesel, etc.) were modelled using the datasets from the Model.

For sorghum, a weighted average of the regional data presented in **Table 21** was compiled to create a single process in the data library. For sugar cane, processes are available for each of the Brazilian states listed in **Table 21**.

Table 21: Geographical scope of internationally grown agricultural crops

State	Sorghum	Sugar cane
Kansas (USA)	✓	
Missouri (USA)	✓	
Nebraska (USA)	✓	
Texas (USA)	✓	
National Average (USA)	✓	
Alagoas (Brazil)		✓
Bahia (Brazil)		✓
Ceará (Brazil)		✓
Espírito Santo (Brazil)		✓
Goiás (Brazil)		✓
Mato Grosso (Brazil)		✓
Mato Grosso do Sul (Brazil)		✓
Maranhão (Brazil)		✓
Minas Gerais (Brazil)		✓
Pará (Brazil)		✓
Paraná (Brazil)		✓
Paraíba (Brazil)		✓
Pernambuco (Brazil)		✓
Piauí (Brazil)		✓
Rio de Janeiro (Brazil)		✓
Rio Grande do Norte (Brazil)		✓
Rio Grande do Sul (Brazil)		✓
Santa Catarina (Brazil)		✓
São Paulo (Brazil)		✓
Sergipe (Brazil)		✓
National Average (Brazil)		✓

The geoFootprint geographical unit of analysis (the most fundamental level at which data are 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. These thresholds are specified in **Table 22.**

Table 22: Grid cell thresholds of crops in geoFootprint

Crop	Threshold [metric ton per grid cell]
Sugar cane	20.00
Sorghum	20.00

Allocation for sorghum and sugar cane

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 and sugar cane

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[19] (WFLDB) and from the ecoinvent database[20] (Weidema et al. 2013). These data 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).

Some data points of key relevance (i.e. harvested area, production volume, yield) are retrieved from the EarthStat[21] 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

[19] 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.

[20] 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.

[21] 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:. https://doi.org/10.1029/2007GB002947.

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 23**.

Table 23: Parameters and data sources in geoFootprint

<table>
<thead>
<tr><th>Parameter</th><th>Data source</th><th>Native resolution</th><th>Scaling method</th><th>Aggregation method</th></tr>
</thead>
<tbody>
<tr><td>Harvested crop area</td><td rowspan="3">EarthStat
(Monfreda, 2008)</td><td rowspan="4">10 x 10 km</td><td rowspan="3">Based on FAOSTAT[22] data evolution from (1999-2001) to (2015-2017)</td><td>Sum</td></tr>
<tr><td>Yield</td><td>Production Volume Weighted Average</td></tr>
<tr><td>Production volume</td><td>Sum</td></tr>
<tr><td>Irrigation water withdrawal</td><td>WFN[23]
(Mekonnen & Hoekstra, 2011)</td><td rowspan="8">n/a</td><td>Production Volume Weighted Average</td></tr>
<tr><td>Surface irrigation</td><td rowspan="3">WFLDB
(Nemecek et al. 2019)</td><td rowspan="3">Country</td><td rowspan="3">Constant at country-level</td></tr>
<tr><td>Sprinkler irrigation</td></tr>
<tr><td>Drip irrigation</td></tr>
<tr><td>Nitrogen fertilizer</td><td rowspan="2">EarthStat
(Monfreda, 2008)</td><td rowspan="3">10x10 km</td><td rowspan="3">Production Volume Weighted Average</td></tr>
<tr><td>Phosphorus fertilizer</td></tr>
<tr><td>Potassium fertilizer</td><td>EarthStat[24]
(Mueller et al., 2012)</td></tr>
<tr><td>Fuel consumption</td><td>WFLDB</td><td>Country</td><td>Constant at country-level</td></tr>
</tbody>
</table>

[22] FAO (2020). FAOSTAT Database. http://www.fao.org/faostat/en/#data/QC.

[23] 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. https://doi.org/10.5194/hessd-8-763-2011.

[24] Mueller ND, Gerber JS, Johnston M, et al (2012) Closing yield gaps through nutrient and water management. Nature 490:254–257. https://doi.org/10.1038/nature11420.

Parameter	Data source	Native resolution	Scaling method	Aggregation method
Crop protection	(Nemecek et al. 2019) Ecoinvent (Weidema et al., 2013)			
SOC stock	ISRIC Soil Grids[25] (Hengl et al., 2014)	10x10 km		Simple Average
Clay content				
Silt content				
Sand content				
Precipitation	GAEZ[26] (FAO, IIASA, 2009)			
Temperature				

The background dataset in WFLDB that was used to model sugar cane includes emissions associated with the practice of pre-harvest burning of sugar cane. These emissions were assumed to occur at 40% of farms in Brazil as modelled in WFLDB[27].

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,

[25] Hengl T, de Jesus JM, MacMillan RA, et al (2014) SoilGrids1km — Global Soil Information Based on Automated Mapping. PLoS ONE 9:e105992. https://doi.org/10.1371/journal.pone.0105992.

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

[27] Bordonal, R., Carvalho, J., Lal, R., Figueiredo, E., Oliveira, B., La Scala Jr, N. (2018). Sustainability of sugarcane production in Brazil. A review. Agronomy for Sustainable Development. 38. 10.1007/s13593-018-0490-x.

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).

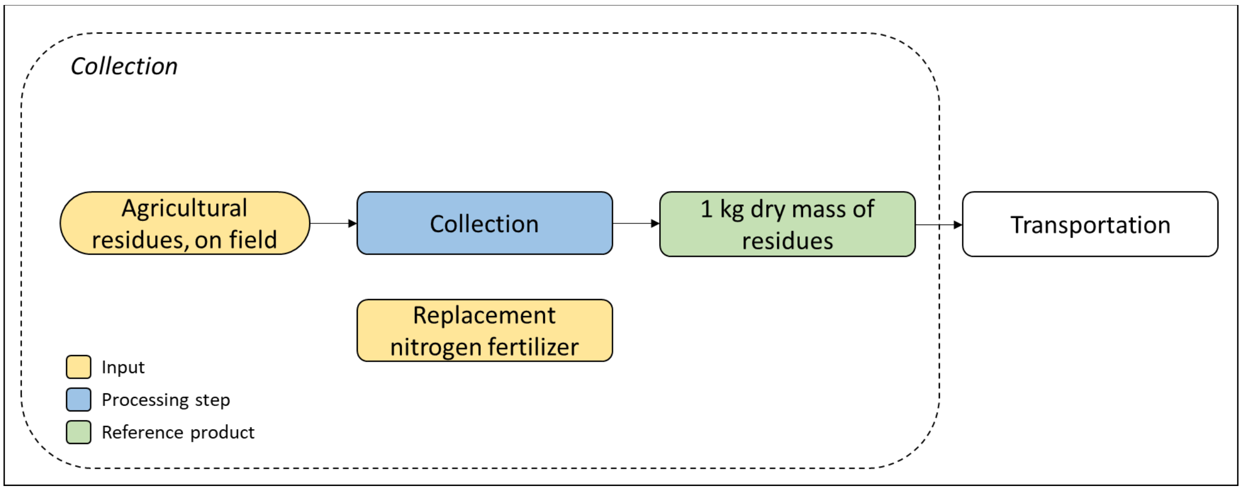

Figure 8: Crop residue collection process overview

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 in **Table 24**.

Table 24: List of main data sources used for the modelling of crop residues

Data type	Data source
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 two generic processes for biogenic and non-biogenic wastes 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:

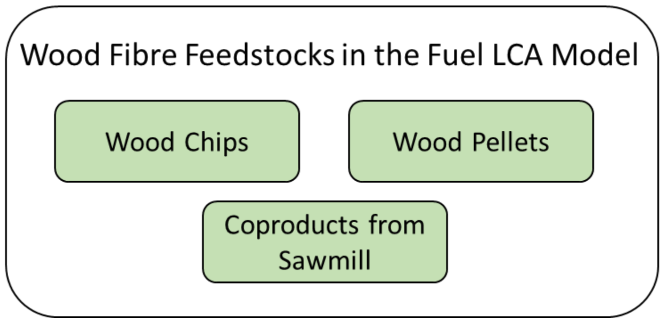

Figure 9 presents the process flow and interaction between the different wood fibre feedstocks included in the Fuel LCA Model. The feedstock production life cycle stage includes harvesting and processing of the aforementioned feedstock sources, and concludes with the production of the main wood fibre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

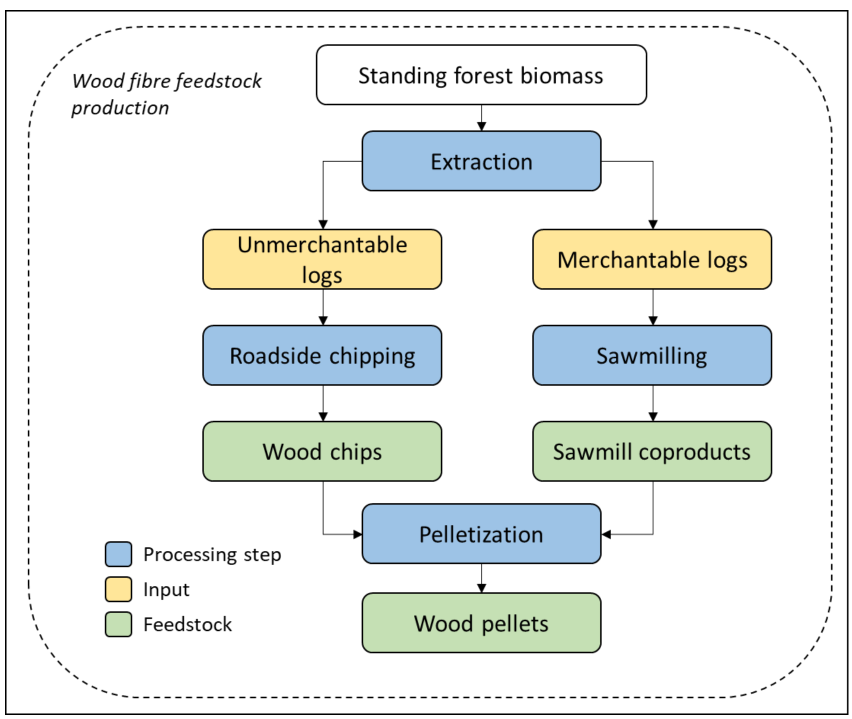

Figure 9: Harvesting and feedstock production process overview for wood fibre feedstocks

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 presented in **Table 25**.

Table 25: List of main data sources used for the modelling of wood fibre feedstock harvesting and production

Data type	Data source
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.* Retrieved from http://www.athenasmi.org/wp-content/uploads/2018/07/CtG-LCA-of-Eastern-Canadian-Surfaced-Dry-Softwood-Lumber.pdf Athena Sustainable Materials Institute. (2018b). *A Cradle-to-Gate Life Cycle Assessment of Eastern Canadian Surfaced Dry Softwood Lumber.* Retrieved from http://www.athenasmi.org/wp-content/uploads/2018/07/CtG-LCA-of-Eastern-Canadian-Surfaced-Dry-Softwood-Lumber.pdf
Unmerchantable logs 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. Yellow grease production

Modelling approach for the production of yellow grease from used cooking oil

Raw UCO is used to produce a rendered UCO called yellow grease. For raw UCO, no impact is associated with its production as it is considered a waste. For yellow grease, the boundary of the process begins with the transport of raw UCO to the processing plant and ends with the production of yellow grease at the processing plant. A trucking distance of 100 km is assumed.

Yellow grease is produced from UCO through a purification process, as illustrated in **Figure 10**. Water is first mechanically removed from the used cooking oil. Any remaining water is then thermally removed.

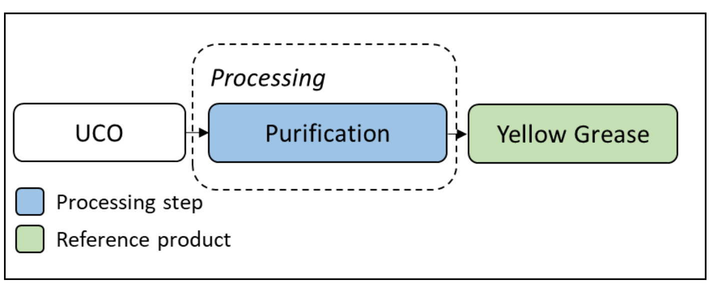

Figure 10: Main processing steps involved in the production of yellow grease from UCO

Geographical scope for the production of yellow grease from UCO

The Model includes processes defined at the provincial and national levels for yellow grease production in Canada. All Canadian processes were based on Canadian data on yellow grease production. 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 the production of yellow grease from UCO

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

Data sources for the production of yellow grease from UCO

Table 26 lists the data source used to model the production of yellow grease.

Table 26: Main data source used for the modelling of the production of yellow grease from UCO

Data type	Data source
UCO Purification	(S&T)[2] Consultants Inc. (2013). GHGenius Model 4.03 Volume 2 Data and Data Sources. Ottawa, ON: Natural Resources Canada.

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 presented in **Figure 11**. In the figure, dashed lines represent co-products transferred between gaseous, liquid and solid fossil fuel life cycle stages. Note that special process routes and other co-products are not represented.

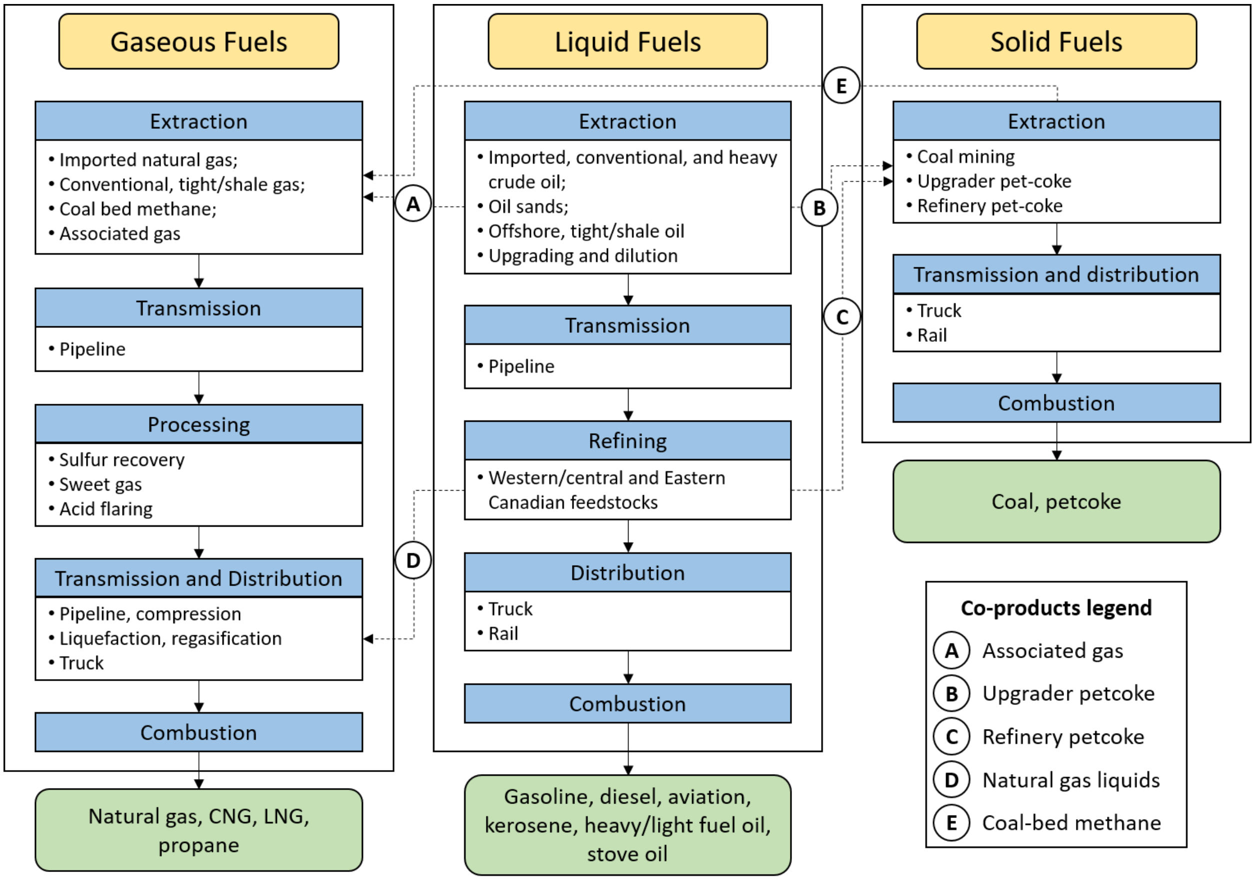

Figure 11: Life cycle stages for gaseous, liquid, and solid fossil fuels included in the Fuel

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; and
- 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 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 taken into account, 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 following sections summarize the modelling approach taken for liquid, gaseous, 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 taken into account 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

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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, https://www.biograce.net/content/ghgcalculationtools/recognisedtool/ Accessed: July 16, 2018.

[30] OCI, 2018. Oil Climate Index, https://oci.carnegieendowment.org/. Accessed: December 1, 2018.

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].

Gaseous fuels

The LCIs for gaseous fuels were calculated based on a production-weighted average of natural gas from Alberta (50.7%), British Columbia (21.7%), and imported natural gas from the United States (28%). The calculation of the default CI values for gaseous fuels was based on the approach used in the National Energy Technology Laboratory (NETL) 2016 study on U.S. natural gas production.[32] Chemical compositions of natural gas for both Alberta and British Columbia were taken into account based on data complied by Greenpath Energy (2019)[33] to model the type and extent of processing and purification required to convert raw gas to pipeline specifications. Natural gas compositions were also used to calculate venting, flaring and fugitive emissions during the extraction and processing stages.

The LCI of imported natural gas from the U.S. was based on the national average CI for natural gas from the NETL 2016 report.[32]

Extraction of gaseous fuels

Natural gas extraction processes were defined for each type of gas resource being developed. The LCI for the extraction stage includes venting, flared and fugitive emissions associated with the various operations (i.e. well completions and workovers, liquids unloading) and different equipment (e.g. water

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31 Environment and Climate Change Canada. 2019. Marine Emissions Inventory Tool.
https://www.canada.ca/en/environment-climate-change/services/managing-pollution/marine-emissions-inventory-tool.html

32 Skone, T. J., and Coauthors, 2016: Life Cycle Analysis of Natural Gas Extraction and Power Generation. http://www.osti.gov/servlets/purl/1480993/

33 Greenpath Energy. 2019. Canadian Natural Gas Data – Collection for the Fuel LCA Modelling Tool. February 2019.

tanks, surface casing vent flow, pneumatic devices). As mentioned earlier, the drilling of wells and the manufacturing and installation of infrastructures were excluded from the system boundary given their negligible contribution to overall impacts.

Processing of gaseous fuels

The process to produce transmission-ready natural gas varies depending on the form of natural gas that is extracted and its composition. The LCI for gas processing includes electricity use, combustion emissions at processing facilities, as well as venting, flaring and fugitive emissions. Both the inventory for Alberta and British Columbia relied on 2011 Alberta data from a detailed GHG emissions inventory of upstream oil and gas operations.[34] An allocation procedure based on energy content was used to allocate GHG emissions to co-products like NGLs (e.g. propane, butane, etc.) which are also produced at gas processing plants.

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 the same as pipeline specification natural gas.

Transmission and distribution of gaseous fuels

The LCA of transmission processes considered the amount of fossil fuels consumed per tonne-km (tkm) of transport, as well as fugitive, flaring and venting emissions related to gas pipelines. The LCI of storage processes includes the amount of natural gas consumed as well as fugitive, venting and flaring emissions.

Table 27: Fuel type of gaseous transportation and storage

Mode of transportation	Fuel used
Pipelines (gas)	Natural gas and electricity
Geological storage	Natural gas
Liquid natural gas storage	Liquid natural gas

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).

For natural gas pipeline transport, GREET data from 2018 was used as a proxy to Canada. Emissions from compressor stations and fugitives are accounted for:

- It is assumed that 98% of the energy for compressor stations comes from natural gas, with the remainder coming from electricity.
- Fugitive emissions are based on 2018 data compiled from Canadian Natural Gas Transmission and Distribution Companies (ORTECH Environmental 2018).

[34] Clearstone Engineering Ltd., 2014: Volume 1: Overview of the GHG Emissions Inventory

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.[35]

Table 28: List of main data sources used for the modelling of gaseous pipeline transportation

Data type	Data source
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. Argonne National Laboratories, 2018, GREET, Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model ORTECH Environmental, 2018, Canadian Natural Gas Transmission and Distribution Companies 2016 Greenhouse Gas Inventory.

Storage

The amount of natural gas consumed for storage as well as storage-related emissions are based on 2016 data from Canadian Energy Partnership for Environmental Innovation (CEPEI).

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.[36] 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.

Combustion emission factors

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 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.

[35] 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.

[36] 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.

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 29: 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
	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.

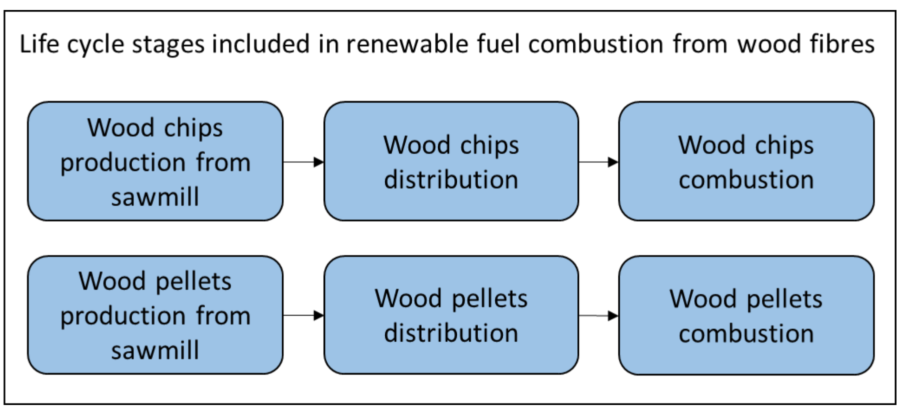

Figure 12: Life cycle stages for renewable fuels based on wood fibre included in the Model

The modelling of distribution to end users is a function of the moisture content equivalent to market level content. **Table 30** 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 30: 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 shown in **Table 31**.

Table 31: List of main data sources used for modelling of distribution and combustion of renewable solid fuels from wood fibres

Data Type	Data source
Distribution (moisture content) and HHV	Natural Resources Canada. Solid Biofuels Bulletin No. 2. Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/files/NRCAN_BB_no2_e13.pdf
Combustion	Government of Canada. (2018). National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada. Retrieved from https://unfccc.int/documents/65715

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 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.

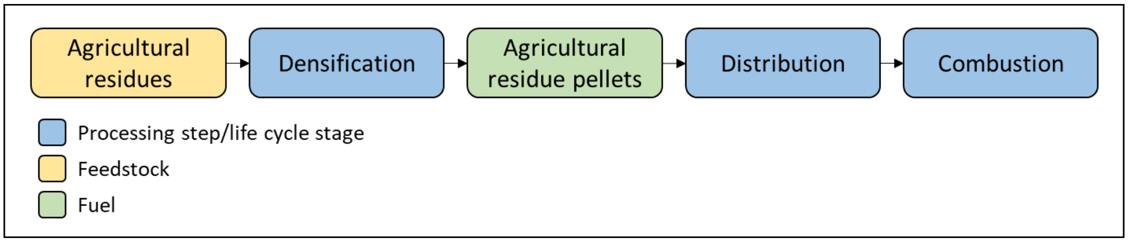

Figure 13: Main processing steps involved in the life cycle for the combustion of agricultural residue pellets

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. **Table 32** shows the main data sources used in the densification process. The combustion process is based on the NIR (2018) and the HHV for agricultural residues are taken from the GREET Model.

Table 32: List of main data sources used for the modelling of agricultural residue pellets combustion

Data type	Data source
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	Argonne National Lab. (2018). GREET.
Combustion	Government of Canada. (2018). National Inventory Report 1990-2016: Greenhouse Gas Sources and Sinks in Canada. Retrieved from https://unfccc.int/documents/65715

3.8. Transportation

3.8.1. Generic transportation

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

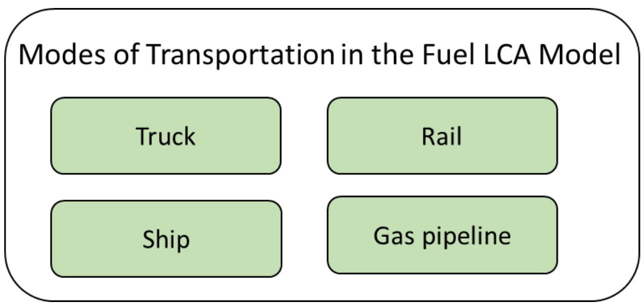

Table 33 shows the corresponding fuels/energy used to power each mode of transportation.

Table 33: Transportation Unit Processes in the Model

Mode of transportation	Fuel/energy used
Truck	Diesel
Train	Diesel
Tanker ship (transoceanic)	Marine diesel
Gas pipeline	Natural gas and electricity

As the fossil fuel consumption of each transportation mode is directly linked to the mass transported and the distance travelled, the functional unit of transportation system processes is 1 tonne-kilometre (tkm - i.e. transport of one metric tonne of feedstock or fuel over a distance of one kilometer). The datasets of transport processes considered the amount of fossil fuel consumed per tkm of transport. As stated in **Chapter 2.3.1**, the manufacturing of fuel transportation 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 **Table 34** listing the main references used.

Train transport

The amount of diesel consumed per tkm of train transport was based on 2016 data from Statistics Canada on the freight mass, the distance travelled and the annual quantity of diesel consumed.

Truck transport

The amount of diesel consumed per tkm of truck transport was calculated based on 2016 fuel efficiency data from the North American Council for Freight Efficiency (NACFE). Average freight and travel distances from Statistics Canada data for 2016 domestic shipments were also used.

Tanker ship transport

The amount of marine diesel consumed per tkm of tanker ship transport was calculated based on 2016 crude shipment data from Canada's MEIT. The fuel production emissions for light fuel oil were used as a proxy for the fuel production emissions of marine diesel.

Gas Pipeline transport

The amount of electricity and of natural gas consumed per tkm of gas pipeline transport was based on 2018 GREET model. Canadian grid mix is used as electricity input.

Table 34: List of main data sources used for the modelling of generic transportation system processes

Data type	Data source
Train	Statistics Canada, 2016, "Table 23-10-0053-01 Railway industry diesel fuel consumption" available at https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2310005301 Statistics Canada, 2017, "Table 23-10-0057-01 Railway industry summary statistics on freight and passenger transportation," available at https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2310005701
Truck	NACFE, 2017, North American Council for Freight Efficiency, 2017 Annual Fleet Fuel Study, available at https://nacfe.org/annual-fleet-fuel-studies/# Statistics Canada, 2016, "Table 23-10-0219-01 Trucking commodity industry activities" available at https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2310021901
Tanker ship	National Marine Emissions Inventory Tool (MEIT), https://www.canada.ca/en/environment-climate-change/services/managing-pollution/marine-emissions-inventory-tool.html
Gas pipeline	Argonne National Lab. (2021). GREET.

3.8.2. Hydrogen transport

Transportation of hydrogen covers the transport of 1 tkm of hydrogen using the specified mode of transportation. The types of hydrogen transportation are summarized in **Table 35**. 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.

Table 35: Types of hydrogen transport processes available in the data library

Mode of transportation	State of hydrogen
Truck	Liquid
Truck	Gaseous
Injection in natural gas pipeline	Gaseous
Injection in dedicated pipeline	Gaseous

Modelling approach for hydrogen transportation

Each sub-section describes the modelling approach taken for that mode of transportation, with **Table 36** listing the main references used.

Truck transport

Truck diesel consumption is directly related to the mass transported and the distance travelled. Hence, the Model uses units of tkm so the process can be used in any fuel pathway. The American Transportation Research Institute (ATRI) provides annual statistics and analysis of the operational costs of trucking. According to the 2021 report, in 2020, the average fuel efficiency was 6.535 miles per gallon (mpg) (2.78 km/litre). Truck transport fuel consumption is modelled using the 2020 fuel efficiency from ATRI and the liquid hydrogen payload from GREET 2021. The data is intended to be representative of Canada. However, all data was sourced from US references (such as GREET, 2021 and ATRI, 2021). The processes can be used regardless of geographical location.

Dedicated pipeline and transport in natural gas pipeline

For hydrogen transport using natural gas pipelines, the 2021 GREET model for natural gas pipeline modelling has been used as a proxy. Weighted average energy to transport 1 barrel 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.

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 2021 GREET model.

Table 36: List of main data sources used for the modelling of hydrogen transportation system processes

Data type	Data source
Truck	Leslie, A. and Murray, D. An Analysis of the Operational Costs of Trucking: 2021 Update. November 2021. American Transportation Research Institute (ATRI). Figure 3: Average MPG by year. 2020. Page 18. Retrieved from: https://truckingresearch.org/wp-content/uploads/2021/11/ATRI-Operational-Cost-of-Trucking-2021-FINAL.pdf GREET 2021 model. Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89. Retrieved from: https://greet.es.anl.gov/
Gas pipeline	GREET 2021 model. Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89. Retrieved from: https://greet.es.anl.gov/
Dedicated pipeline	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 2021 model. Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89. Retrieved from: https://greet.es.anl.gov/

3.8.3. 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 transportation section and as stated in **Chapter 2.3.1**, the manufacturing of fuel transportation infrastructure (i.e., trucks, ships, and rail) was excluded from the Model. Also excluded are any on-site transportation 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 transportation, with **Table 37** listing the main references used.

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 transportation 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)
- Transportation CIs (**Chapter 3.8.1**)

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. Transportation 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 transportation 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 transportation distances in Western and Eastern Canada were estimated based on ECCC expert judgment.

LCIF distribution

LCIF distribution includes the life cycle stages that bridges fuel conversion and use by the end-users. This includes the transportation 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.

Table 37: List of main data sources used for the modelling of predefined transportation system processes

Data type	Data source
Feedstock transport	Yield and allocation of the feedstock: 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. Moisture content of feedstock: ECCC internal database Transportation CIs: see **Chapter 3.8.1**
Fossil fuel distribution	Provincial data on natural gas consumption: NEB, 2017b, Canadian Marketable Natural Gas Production - Open Government Portal, 2017, available at https://open.canada.ca/data/en/dataset/26cadec4-d316-4022-97fb-8e49dd768b6d Accessed: Accessed December 1, 2019. Data for propane distribution: National Energy Board and Competition Bureau. 2014. Propane Market Review - Final Report. https://www.nrcan.gc.ca/energy/energy-sources-distribution/refining-sector-canada/propane-market-review-final-report/15927#supchain Enbridge Website: https://www.enbridge.com/Map.aspx#map:infrastructure,crudeInfrastructure,NGL The Conference Board of Canada. 2021. Canada's Propane Supply Chain, Reliability and resilience. https://propane.ca/wp-content/uploads/2021/10/CoBC-Market-study-2021.pdf 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. https://propane.ca/wp-content/uploads/2018/12/CPA_Propane_Market_Study_OVERVIEW_CBoC_EN_2018.pdf ORTECH Environmental, 2018, Canadian Natural Gas Transmission and Distribution Companies 2016 Greenhouse Gas Inventory
LCIF distribution	Liquid LCIF: Based on ECCC assumption and expert input Gaseous LCIF: see **Chapter 3.8.2, 3.8.4, and 3.8.5**

3.8.4. Renewable natural gas transport

Transport of 1 tkm of RNG in Canada was modelled using pipelines and diesel trucks.

Modelling approach for renewable natural gas transportation

Each sub-section describes the modelling approach taken for that mode of transportation, with **Table 38** listing the main references used.

Truck transport

Boil-off emissions during truck transport of RNG are based on GREET 2021, using LNG transportation by truck as a proxy. The truck's diesel consumption is directly related to the mass transported and the distance traveled. Hence, the Model uses units of t-km (metric tonne*kilometers) so the process can be used in any fuel pathway. The ATRI provides annual statistics and analysis of the operational costs of trucking. According to the 2021 report, in 2020, the average fuel efficiency was 6.535 mpg (2.78 km/liter). Truck transport fuel consumption is modelled using the 2020 fuel efficiency from ATRI and payloads by commodity from GREET 2021. The LNG payload was used as a proxy at 15 tonnes. At 6.535 mpg of fuel efficiency, this results in a diesel combusted of 1.02 MJ per tkm for LNG (RNG) freight. These calculations take into consideration average loading, therefore, there is no disaggregation between empty, partial, or fully loaded trucks. This process is intended to be representative of Canada. However, all data was sourced from U.S. references (GREET 2021). No allocation procedure was performed.

Pipeline transport

Flaring, fugitive, venting and emergency response emissions were included to calculate the CI of RNG transport. The energy consumption (i.e. electricity and natural gas) required for pipeline transport was modelled in the similar way as the generic pipeline transport process. Transportation data on fugitive, venting and flaring emissions from natural gas pipelines is based on actual data from CEPEI (ORTECH 2018).

Table 38: List of main data sources used for the modelling of RNG transportation system processes

Data type	Data source
Truck	Leslie, A. and Murray, D. An Analysis of the Operational Costs of Trucking: 2021 Update. November 2021. American Transportation Research Institute (ATRI). Figure 3: Average MPG by year. 2020. Page 18. Retrieved from: https://truckingresearch.org/wp-content/uploads/2021/11/ATRI-Operational-Cost-of-Trucking-2021-FINAL.pdf GREET 2021 model. Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89. Retrieved from: https://greet.es.anl.gov/
Gas pipeline	GREET 2021 model. Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89. Retrieved from: https://greet.es.anl.gov/ ORTECH Environmental, 2018, Canadian Natural Gas Transmission and Distribution Companies 2016 Greenhouse Gas Inventory

3.8.5. Renewable propane transport

Overview of transportation modelling

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

Modelling approach for renewable propane transportation

The below section describes the modelling approach taken, with **Table 39** listing the main references used.

Pipeline transport

Fugitive emissions, emergency response emissions and venting emissions were excluded for renewable propane transport and only flaring emissions (i.e. biogenic CO_2, biogenic CH_4 and N_2O) were included. Mean values for emissions were calculated from transmission and distribution data on flaring emissions from natural gas pipelines using data from CEPEI (ORTECH Environmental, 2018). 2021 GREET natural gas pipeline model has been used as a proxy for renewable propane transport. Canadian average grid was applied to reflect the emissions due to the average electricity usage across Canada. Weighted average energy to transport 1 barrel 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.

Table 39: List of main data sources used for the modelling of renewable propane transportation system processes

Data type	Data source
Gas pipeline	GREET 2021 model. Tab 'T&D'. 7) Energy Intensity of Pipeline Transportation: Btu/ton-mile. Cell B89. Retrieved from: https://greet.es.anl.gov/ ORTECH Environmental, 2018, Canadian Natural Gas Transmission and Distribution Companies 2016 Greenhouse Gas Inventory

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**.

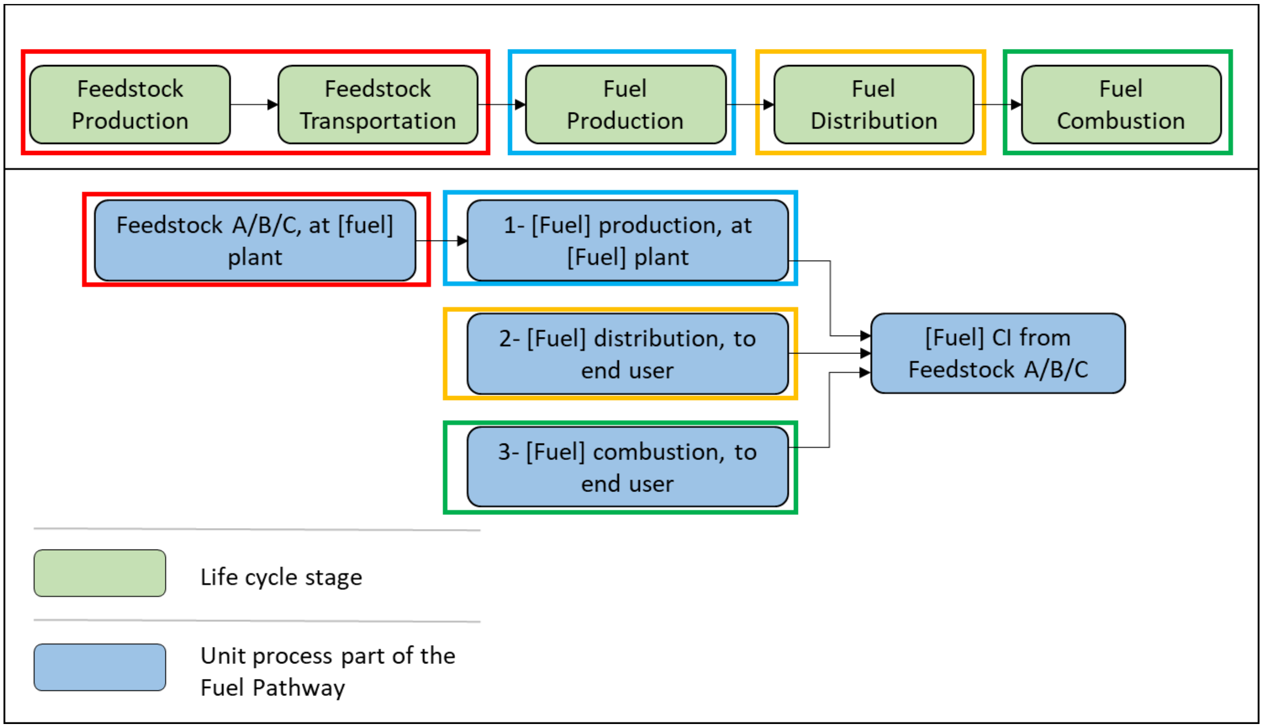

Figure 14: Top: five main life cycle stages. Bottom: general structure of fuel pathways in the Model database

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. For example, there are three feedstock production unit processes created to allow for different feedstocks to be modelled 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.

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**.

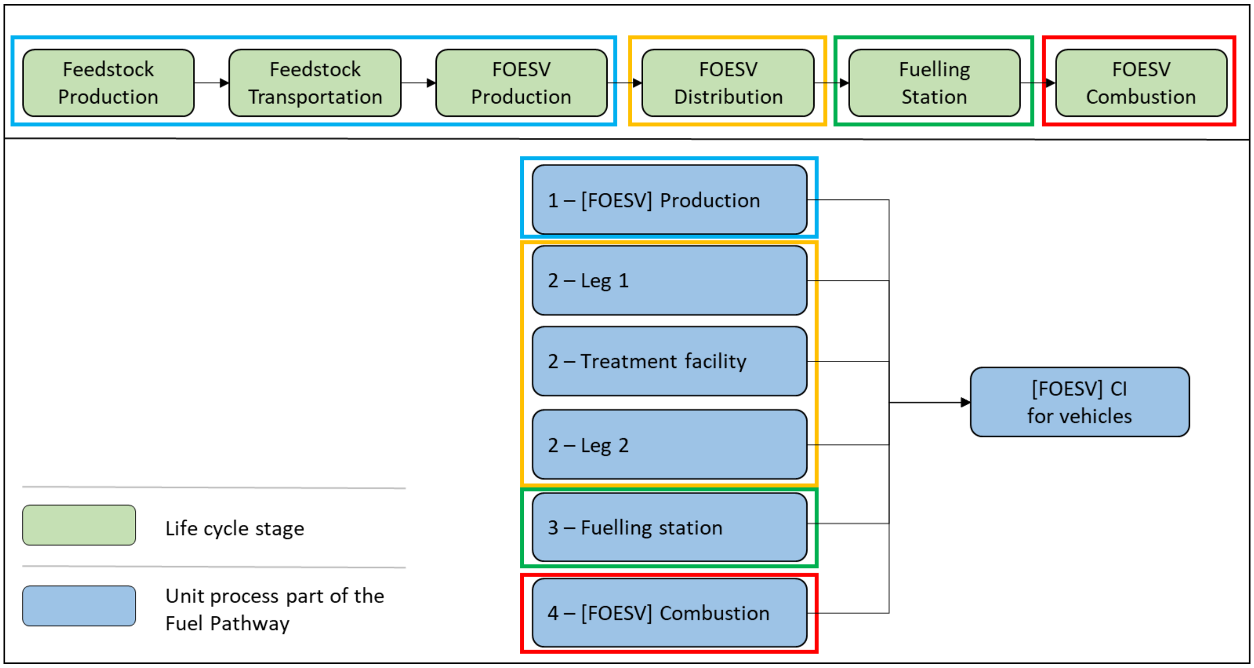

Figure 15: Top: six life cycle stages for FOESV. Bottom: structure of a Fuel pathway dedicated to FOESV in the Model database

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 the same way as those available in the data library (**Chapter 3.5.1**). The CI was calculated excluding electricity inputs. The emission factors for the results were then included as outputs of the configurable processes, and a dummy flow for the electricity input was added. The dummy flow can be replaced by users to match their electricity grid mix.

4.2.2. Modelling approach for CCS configurable processes

The carbon capture and storage (CCS) configurable processes were modelled for two fuel pathways (i.e. the "Biogenic carbon dioxide (CO_2) capture, at bioethanol plant" for the bioethanol from corn fuel pathway and the "Fossil carbon dioxide (CO_2) capture, at hydrogen SMR plant" for the hydrogen from SMR fuel pathway). These configurable processes include predefined input values for the amount of additional electricity and thermal energy needed for the carbon capture process and transport (input values were developed by the Pembina Institute and are based on the Shell Quest Project Engineering and Operating Data). The processes also include fugitive emissions associated with the capture, transport and injection process as a predefined output (output values are based on published reported/estimated emissions). **Table 40** shows the main data sources used to model the CCS configurable processes. The processes do not include energy related to injection in geological formation as the contribution of this activity to GHG emissions is considered negligible compared to the other sources of emissions. These predefined input and output values of the CCS processes can be updated with user specific data.

In the CCS process called "Biogenic carbon dioxide (CO_2) capture, at bioethanol plant" the captured biogenic CO_2 emissions are represented by a negative flow of fossil CO_2 emissions. This is done to reflect the permanent storage of biogenic CO_2 emissions. Fossil CO_2 emissions are used even though biogenic CO_2 emissions are captured. The reduction in emissions would otherwise not impact the CI of the bioethanol production with CCS as the GWP of biogenic CO_2 emissions is set to 0.

In the CCS process called "Fossil carbon dioxide (CO_2) capture, at hydrogen SMR plant", the captured fossil CO_2 emissions are set to zero as it is assumed that the net reported fossil CO_2 emissions in the hydrogen fuel production pathway already accounts for the captured emissions. This ensures that the benefit of CCS is not double counted. If the fossil CO_2 emissions that would have been emitted in absence of a CCS process are included in other unit processes of the fuel pathway, this negative flow of CO_2 can be set to -1 by the user to cancel these fossil CO_2 emissions.

Both configurable CCS processes have a functional unit of 1 kg of captured CO_2. To represent the idea of a capture process, both processes are built as a waste treatment process, with a waste flow of 1 kg of CO_2 captured (please see Chapter 6.2.3 of the *Fuel LCA Model User Manual* for the description of a waste flow). These CCS waste treatment processes can be connected to the bioethanol or hydrogen fuel production pathways by adding the "CO_2 captured" waste flow of the respective process to the list of output flows of the "[fuel] production, at [fuel] plant" process. Additionally, the dummy electricity flow can be replaced with the desired grid mix. The metadata of the CCS configurable processes provide detailed instructions on how to use them in different contexts.

Table 40: List of main data sources used for the modelling of CCS unit processes

Data type	Data source
CCS	Shell Canada Ltd. (2011). Quest Carbon Capture and Storage Project: annual report 2011. Heat and material balance. Available online: 03.05.2013.BDEPA13HMBs.pdf (alberta.ca) Shell Canada Ltd. (2013). Quest Carbon Capture and Storage Project: annual report 2013. Process flow diagram: hydrogen manufacturing unit. Available online: 03.05.2013.BDEPA13HMBs.pdf (alberta.ca) Shell Canada Ltd. (2017). Quest Carbon Capture and Storage Project: Quest Power Efficiency and Parasitic Loss Summary. Available online: CO2 Pipeline Operations Report (alberta.ca). Shell Canada Ltd. (2021). Quest Carbon Capture and Storage Project: Quest GHG and Energy Report for 2020. Available online: Quest GHG and energy report 2020 (alberta.ca) Enhance Energy Inc. (2021). Knowledge Sharing Report. Available online: Knowledge sharing. Division B detailed report and appendices. Calendar year 2020 (alberta.ca)

4.2.3. Modelling approach for corn oil configurable processes

The corn oil configurable process was modelled as a co-product of dry mill ethanol production from the fermentation of corn feedstock. The boundary of corn oil production begins with the corn 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.

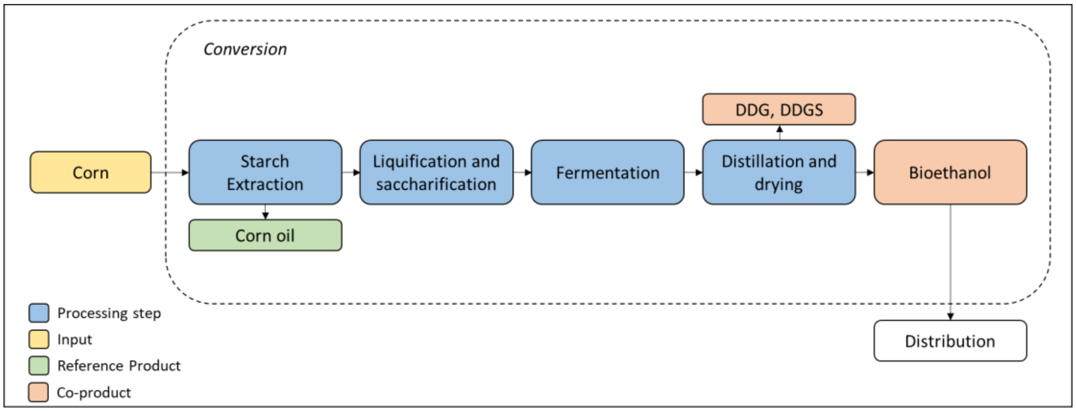

Figure 16: Main processing steps for the production of corn oil in Canada and America

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.

Table 41: List of main data sources used for the modelling of the production of corn oil

Data type	Data source
Corn oil production	Argonne National Lab. (2019). GREET. https://greet.es.anl.gov/index.php

The configurable process was modelled by calculating the LCI of the corn oil production process excluding the electricity inputs. The LCI results were then added to the output of the configurable process, while an electricity dummy flow was added as an input. The user can replace the dummy flow with an electricity flow representing their desired grid mix.

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 a Canadian 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, transportation, 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.

The CRSC reports did not contain information for camelina. Nevertheless, most of the LCI for camelina was built using the same data sources from the CRSC reports and the modelling approach remained the same. Data gaps were filled in using literature data to supplement missing information. **Table 42** details the main data sources.

Table 42: List of main data sources used for the modelling of camelina cultivation modelling

Data type	Data source
Yields	2019 data from Smart Earth Seeds
Fertilizer rates	2019 Crop Planning Guide from Saskatchewan
Energy use	Used energy use data from canola as proxy based on the Prairie Crop Energy Model and 2011 Agriculture survey

The provincial data used for the three oilseed crops from the CRSC reports is shown in **Table 43**.

Table 43: 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										✓
Canola	✓	✓	✓	✓						✓
Soybean			✓	✓		✓	✓	✓	✓	

After oilseed cultivation, oilseed transportation was modelled by truck over an assumed distance of 100 km. 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**.

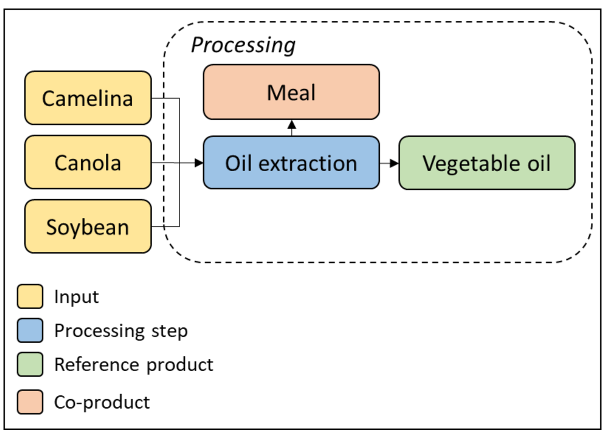

Figure 17: Main processing steps involved in the extraction of vegetable oil feedstock from oilseeds

Oil extraction data was compiled from U.S and Canadian literature review for camelina oil, canola oil and soybean oil production.

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.

The data sources used in modelling oil extraction from oilseeds are presented in **Table 44**. 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.

Table 44: List of main data sources used for the modelling of oil extraction from oilseeds

Data Type	Data Source
Oilseed production	Crop-specific CRSC reports on canola and soybeans: (S&T)2 Consultants. (2017). *Carbon Footprint For Canadian Canola.* Winnipeg, MB: Canadian Roundtable on Sustainable Crops. (S&T)2 Consultants. (2017). *Carbon Footprint For Canadian Soybeans.* Winnipeg, MB: Canadian Roundtable on Sustainable Crops. (S&T)2 Consultants Inc. (2017c). *Carbon Footprints for Major Canadian Grains Methodology Report.* Winnipeg, MB: Canadian Roundtable on Sustainable Crops. Statistics Canada. Table 32-10-0359-01 Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. Available at: https://doi.org/10.25318/3210035901-eng
Oil extraction	Miller, P., & Kumar, A. (2013). Development of emission parameters and net energy ratio for renewable diesel from Canola and Camelina. *Energy, 58*, 426-437. Shonnard, D., Williams, L., & Kalnes, T. (n.d.). (2010). Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. *Environ. Prog. Sustainable Energy, 29*, 382-392 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 technology, 251, 249-258.

The configurable process was modelled by calculating the LCI of the oilseed extraction process excluding the electricity inputs for oilseed extraction. The LCI results were then added to the output of the configurable process, while an electricity dummy flow was added as an input. The user can replace the dummy flow with an electricity flow representing their desired grid mix.

4.2.6. Modelling approach for yellow grease configurable processes

The yellow grease configurable processes were modelled the same way as those available in the data library (**Chapter 3.5.1**). The LCI was calculated excluding electricity inputs. The LCI results were then added to the output of the configurable process, while an electricity dummy flow was added as an input. The user can replace the dummy flow with an electricity flow representing their desired grid mix.

Appendix A GHG impact factors

The Model includes several GHGs as elementary flows. The GHGs included in the Model is displayed in **Table 45**. It includes the GWP of each GHG, adapted from the IPCC's AR5.

Table 45: GWP 100-year of GHGs. Adapted from the IPCC's AR5[37]

Acronym, Common Name or Chemical Name	Chemical Formula	GWP 100-year	Uncertainty
Carbon dioxide	CO_2	1	
Methane (biogenic)	CH_4	28	11.2
Fossil methane	CH_4	30	12
Nitrous Oxide	N_2O	265	79.5
Chlorofluorocarbons			
CFC-11	CCl_3F	4660	1631
CFC-12	CCl_2F_2	10200	3060
CFC-13	$CClF_3$	13900	2780
CFC-113	CCl_2FCClF_2	5820	1164
CFC-114	$CClF_2CClF_2$	8590	1718
CFC-115	$CClF_2CF_3$	7670	1534
Hydrochlorofluorocarbons			
HCFC-21	$CHCl_2F$	148	59.2
HCFC-22	$CHClF_2$	1760	704
HCFC-122	$CHCl_2CF_2Cl$	59	23.6
HCFC-122a	$CHFCLClFCl_2$	258	103.2
HCFC-123	$CHCl_2CF_3$	79	31.6
HCFC-123a	$CHClFCF_2Cl$	370	148
HCFC-124	$CHClFCF_3$	527	210.8
HCFC-132c	CH_2FCFCl_2	338	135.2
HCFC-141b	CH_3CCl_2F	782	312.8
HCFC-142b	CH_3CClF_2	1980	495
HCFC-225ca	$CHCl_2CF_2CF_3$	127	50.8
HCFC-225cb	$CHClFCF_2CClF_2$	525	210
(E)-1-Chloro-3,3,3-trifluoroprop-1-ene	trans-CF_3CH=CHCl	1	0.04
Hydrofluorocarbons			
HFC-23	CHF_3	12400	2480
HFC-32	CH_2F_2	677	270.8
HFC-41	CH_3F	116	46.4
HFC-125	CHF_2CF_3	3170	792.5
HFC-134	CHF_2CHF_2	1120	448

[37] 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.

Acronym, Common Name or Chemical Name	Chemical Formula	GWP 100-year	Uncertainty
HFC-134a	CH_2FCF_3	1300	455
HFC-143	CH_2FCHF_2	328	131.2
HFC-143a	CH_3CF_3	4800	960
HFC-152	CH_2FCH_2F	16	6.4
HFC-152a	CH_3CHF_2	138	55.2
HFC-161	CH_3CH_2F	4	0.16
HFC-227ca	$CF_3CF_2CHF_2$	2640	660
HFC-227ea	CF_3CHFCF_3	3350	837.5
HFC-236cb	$CH_2FCF_2CF_3$	1210	484
HFC-236ea	CHF_2CHFCF_3	1330	532
HFC-236fa	$CF_3CH_2CF_3$	8060	1612
HFC-245ca	$CH_2FCF_2CHF_2$	716	286.4
HFC-245cb	$CF_3CF_2CH_3$	4620	924
HFC-245ea	$CHF_2CHFCHF_2$	235	94
HFC-245eb	$CH_2FCHFCF_3$	290	116
HFC-245fa	$CHF_2CH_2CF_3$	858	343.2
HFC-263fb	$CH_3CH_2CF_3$	76	30.4
HFC-272ca	$CH_3CF_2CH_3$	144	57.6
HFC-329p	$CHF_2CF_2CF_2CF_3$	2360	590
HFC-365mfc	$CH_3CF_2CH_2CF_3$	804	321.6
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	1650	412.5
(Z)-HFC-1336	$CF_3CH{=}CHCF_3$(Z)	2	0.08
Chlorocarbons and Hydrochlorocarbons			
Methyl chloroform	CH_3CCl_3	160	64
Carbon tetrachloride	CCl_4	1730	432.5
Methyl chloride	CH_3Cl	12	4.8
Methylene chloride	CH_2Cl_2	9	3.6
Chloroform	$CHCl_3$	16	6.4
Bromocarbons, Hydrobromocarbons and Halons			
Methyl bromide	CH_3Br	2	0.8
Methylene bromide	CH_2Br_2	1	0.4
Halon-1201	$CHBrF_2$	376	150.4
Halon-1202	CBr_2F_2	231	92.4
Halon-1211	$CBrClF_2$	1750	437.5
Halon-1301	$CBrF_3$	6290	1258
Halon-2301	CH_2BrCF_3	173	69.2
Halon-2311 / Halothane	$CHBrCLClF_3$	41	16.4
Halon-2401	$CHFBrCF_3$	184	73.6
Halon-2402	$CBrF_2CBrF_2$	1470	367.5
Fully Fluorinated Species			
Nitrogen trifluoride	NF_3	16100	3220
Sulphur hexafluoride	SF_6	23500	4700
(Trifluoromethyl) sulphur pentafluoride	SF_5CF_3	17400	3480
Sulphuryl fluoride	SO_2F_2	4090	1022.5

Acronym, Common Name or Chemical Name	Chemical Formula	GWP 100-year	Uncertainty
PFC-14	CF_4	6630	1326
PFC-116	C_2F_6	11100	2220
PFC-c216	c-C_3F_6	9200	1840
PFC-218	C_3F_8	8900	1780
PFC-318	c-C_4F_8	9540	1908
PFC-31-10	C_4F_{10}	9200	1840
Perfluorocyclopentene	c-C_5F_8	2	0.08
PFC-41-12	n-C_5F_{12}	8550	1710
PFC-51-14	n-C_6F_{14}	7910	1582
PFC-61-16	n-C_7F_{16}	7820	1564
PFC-71-18	C_8F_{18}	7620	1524
PFC-91-18	$C_{10}F_{18}$	7190	1438
Perfluorodecalin (cis)	Z-$C_{10}F_{18}$	7240	1448
Perfluorodecalin (trans)	E-$C_{10}F_{18}$	6290	1258
Perfluorobut-2-ene	$CF_3CF{=}CFCF_3$	2	0.08
Halogenated Alcohols and Ethers			
HFE-125	CHF_2OCF_3	12400	2480
HFE-134 (HG-00)	CHF_2OCHF_2	5560	1390
HFE-143a	CH_3OCF_3	523	209.2
HFE-227ea	$CF_3CHFOCF_3$	6450	1290
HCFE-235ca2 (enflurane)	CHF_2OCF_2CHFCl	583	233.2
HCFE-235da2 (isoflurane)	$CHF_2OCHCLCIF_3$	491	196.4
HFE-236ca	$CHF_2OCF_2CHF_2$	4240	1060
HFE-236ea2 (desflurane)	$CHF_2OCHFCF_3$	1790	716
HFE-236fa	$CF_3CH_2OCF_3$	979	391.6
HFE-245cb2	$CF_3CF_2OCH_3$	654	261.6
HFE-245fa1	$CHF_2CH_2OCF_3$	828	331.2
HFE-245fa2	$CHF_2OCH_2CF_3$	812	324.8
2,2,3,3,3-Pentafluoropropan-1-ol	$CF_3CF_2CH_2OH$	19	7.6
HFE-254cb1	$CH_3OCF_2CHF_2$	301	120.4
HFE-263fb2	$CF_3CH_2OCH_3$	1	0.04
HFE-263m1	$CF_3OCH_2CH_3$	29	11.6
HFE-329mcc2	$CHF_2CF_2OCF_2CF_3$	3070	767.5
HFE-338mmz1	$(CF_3)_2CHOCHF_2$	2620	655
HFE-338mcf2	$CF_3CH_2OCF_2CF_3$	929	371.6
Sevoflurane (HFE-347mmz1)	$(CF_3)_2CHOCH_2F$	216	86.4
HFE-347mcc3 (HFE-7000)	$CH_3OCF_2CF_2CF_3$	530	212
HFE-347mcf2	$CHF_2CH_2OCF_2CF_3$	854	341.6
HFE-347pcf2	$CHF_2CF_2OCH_2CF_3$	889	355.6
HFE-347mmy1	$(CF_3)_2CFOCH_3$	363	145.2
HFE-356mec3	$CH_3OCF_2CHFCF_3$	387	154.8
HFE-356mff2	$CF_3CH_2OCH_2CF_3$	17	0.68
HFE-356pcf2	$CHF_2CH_2OCF_2CHF_2$	719	287.6
HFE-356pcf3	$CHF_2OCH_2CF_2CHF_2$	446	178.4

Acronym, Common Name or Chemical Name	Chemical Formula	GWP 100-year	Uncertainty
HFE-356pcc3	$CH_3OCF_2CF_2CHF_2$	413	165.2
HFE-356mmz1	$(CF_3)_2CHOCH_3$	14	0.56
HFE-365mcf2	$CF_3CF_2OCH_2CH_3$	58	23.2
HFE-374pc2	$CHF_2CF_2OCH_2CH_3$	627	250.8
2,2,3,3,4,4,5,5-Octafluorocyclopentanol	$-(CF_2)_4CH(OH)-$	13	5.2
HFE-43-10pccc124 (H-Galden 1040x, HG-11)	$CHF_2OCF_2OC_2F_4OCHF_2$	2820	705
HFE-449s1 (HFE-7100)	$C_4F_9OCH_3$	421	168.4
n-HFE-7100	$n-C_4F_9OCH_3$	486	194.4
i-HFE-7100	$i-C_4F_9OCH_3$	407	162.8
HFE-569sf2 (HFE-7200)	$C_4F_9OC_2H_5$	57	22.8
n-HFE-7200	$n-C_4F_9OC_2H_5$	65	26
i-HFE-7200	$i-C_4F_9OC_2H_5$	44	17.6
HFE-236ca12 (HG-10)	$CHF_2OCF_2OCHF_2$	5350	1337.5
HFE-338pcc13 (HG-01)	$CHF_2OCF_2CF_2OCHF_2$	2910	1164
1,1,1,3,3,3-Hexafluoropropan-2-ol	$(CF_3)_2CHOH$	182	72.8
HG-02	$HF_2C–(OCF_2CF_2)_2–OCF_2H$	2730	1092
HG-03	$HF_2C–(OCF_2CF_2)_3–OCF_2H$	2850	1140
HG-20	$HF_2C–(OCF_2)_2–OCF_2H$	5300	1325
HG-21	$HF_2C–OCF_2CF_2OC-F_2OCF_2O–CF_2H$	3890	972.5
HG-30	$HF_2C–(OCF_2)_3–OCF_2H$	7330	1832.5
1-Ethoxy-1,1,2,2,3,3,3-heptafluoropropane	$CF_3CF_2CF_2OCH_2CH_3$	61	24.4
1,1,2,2-Tetrafluoro-1-(fluoromethoxy)ethane	$CH_2FOCF_2CF_2H$	871	348.4
2-Ethoxy-3,3,4,4,5-pentafluorotetrahydro-2,5-bis[1,2,2,2- tetrafluoro-1-(trifluoromethyl)ethyl]-furan	$C_{12}H_5F_{19}O_2$	56	22.4
Fluoro(methoxy)methane	CH_3OCH_2F	13	0.52
Difluoro(methoxy)methane	CH_3OCHF_2	144	57.6
Fluoro(fluoromethoxy)methane	CH_2FOCH_2F	130	52
Difluoro(fluoromethoxy)methane	CH_2FOCHF_2	617	246.8
Trifluoro(fluoromethoxy)methane	CH_2FOCF_3	751	300.4
HG’-01	$CH_3OCF_2CF_2OCH_3$	222	88.8
HG’-02	$CH_3O(CF_2CF_2O)_2CH_3$	236	94.4
HG’-03	$CH_3O(CF_2CF_2O)_3CH_3$	221	88.4
HFE-329me3	$CF_3CFHCF_2OCF_3$	4550	1137.5
2-Chloro-1,1,2-trifluoro-1-methoxyethane	CH_3OCF_2CHFCl	122	48.8
PFPMIE (perfluoropolymethylisopropyl ether)	$CF_3OCF(CF_3) CF_2OCF_2OCF_3$	9710	1942
Trifluoromethyl formate	$HCOOCF_3$	588	235.2
Perfluoroethyl formate	$HCOOCF_2CF_3$	580	232
Perfluoropropyl formate	$HCOOCF_2CF_2CF_3$	376	150.4
Perfluorobutyl formate	$HCOOCF_2CF_2CF_2CF_3$	392	156.8

Acronym, Common Name or Chemical Name	Chemical Formula	GWP 100-year	Uncertainty
2,2,2-Trifluoroethyl formate	$HCOOCH_2CF_3$	33	13.2
3,3,3-Trifluoropropyl formate	$HCOOCH_2CH_2CF_3$	17	6.8
1,2,2,2-Tetrafluoroethyl formate	$HCOOCHFCF_3$	470	188
1,1,1,3,3,3-Hexafluoropropan-2-yl formate	$HCOOCH(CF_3)_2$	333	133.2
Perfluorobutyl acetate	$CH_3COOCF_2CF_2CF_2CF_3$	2	0.08
Perfluoropropyl acetate	$CH_3COOCF_2CF_2CF_3$	2	0.08
Perfluoroethyl acetate	$CH_3COOCF_2CF_3$	2	0.08
Trifluoromethyl acetate	CH_3COOCF_3	2	0.08
Methyl carbonofluoridate	$FCOOCH_3$	95	38
1,1-Difluoroethyl carbonofluoridate	$FCOOCF_2CH_3$	27	10.8
1,1-Difluoroethyl 2,2,2-trifluoroacetate	$CF_3COOCF_2CH_3$	31	12.4
Ethyl 2,2,2-trifluoroacetate	$CF_3COOCH_2CH_3$	1	0.04
2,2,2-Trifluoroethyl 2,2,2-trifluoroacetate	$CF_3COOCH_2CF_3$	7	0.28
Methyl 2,2,2-trifluoroacetate	CF_3COOCH_3	52	20.8
Methyl 2,2-difluoroacetate	HCF_2COOCH_3	3	0.12
Difluoromethyl 2,2,2-trifluoroacetate	$CF_3COOCHF_2$	27	10.8
2,2,3,3,4,4,4-Heptafluorobutan-1-ol	$C_3F_7CH_2OH$	34	13.6
1,1,2-Trifluoro-2-(trifluoromethoxy)-ethane	$CHF_2CHFOCF_3$	1240	496
1-Ethoxy-1,1,2,3,3,3-hexafluoropropane	$CF_3CHFCF_2OCH_2CH_3$	23	9.2
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	$CF_3CF_2CF_2OCHFCF_3$	6490	1298
2,2,3,3-Tetrafluoro-1-propanol	$CHF_2CF_2CH_2OH$	13	0.52
2,2,3,4,4,4-Hexafluoro-1-butanol	$CF_3CHFCF_2CH_2OH$	17	0.68
2,2,3,3,4,4,4-Heptafluoro-1-butanol	$CF_3CF_2CF_2CH_2OH$	16	6.4
2,2-Difluoroethanol	CHF_2CH_2OH	3	0.12
2,2,2-Trifluoroethanol	CF_3CH_2OH	20	8
1,1'-Oxybis[2-(difluoromethoxy)-1,1,2,2-tetrafluoroethane	$HCF_2O(CF_2CF_2O)_2CF_2H$	4920	1230
1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12-hexa-decafluoro-2,5,8,11-Tetraoxadodecane	$HCF_2O(CF_2CF_2O)_3CF_2H$	4490	1122.5
1,1,3,3,4,4,6,6,7,7,9,9,10,10,12,12,13,13,15,15-eico-safluoro-2,5,8,11,14-Pentaoxapentadecane	$HCF_2O(CF_2CF_2O)_4CF_2H$	3630	907.5

Appendix B 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 46: Supplemental feedstock conversion values

Feedstock category	Feedstock type	Density	Unit	Data source
Grains	Barley	41.76	dry lbs/bushel	GHGenius 5.01e (tab "Fuel Char")
	Corn	47.60	dry lbs/bushel	GHGenius 5.01e (tab "Fuel Char")
	Wheat (non-durum)	52.20	dry lbs/bushel	GHGenius 5.01e (tab "Fuel Char")
Field peas	Field peas	52.20	dry lbs/bushel	GHGenius 5.01e (tab "Fuel Char")
Vegetable Oils and animal fat	Animal fat	0.884	kg/L	GHGenius 5.01e (tab "Fuel Char"), based on density for tallow
	Corn oil	0.915	kg/L	GHGenius 5.01e (tab "Fuel Char"), based on density for canola oil
	Oil from oilseeds	0.915	kg/L	GHGenius 5.01e (tab "Fuel Char"), based on density for canola oil
	Used cooking oil (UCO)	0.910	kg/L	GHGenius 5.01e (tab "Fuel Char"), based on density for used oil
	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). Available at: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/NRCAN_BB_no2_e_indd.pdf
	Wood pellets, from sawmill co-products	34.04	dry lbs/ft3	
	Wood pellets, from unmerchantable logs	34.04	dry lbs/ft3	

Table 47: 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
	HHV (MJ/L)	23.42	Calculated
	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
	HHV (MJ/L)	35.18	calculated
	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)
	HHV (MJ/L)	34.92	calculated
	Density (kg/m^3)	748.93	Calculated based on GREET 2018. Refer to "HHV GREET Calcs.xlsx"
Sustainable aviation fuel (SAF)	HHV (MJ/kg)	46.32	Assumed to be the same as fossil jet fuel
	HHV (MJ/L)	37.40	calculated
	Density (kg/m^3)	807.40	Assumed to be the same as fossil jet fuel
Renewable propane (gaseous)	HHV (MJ/kg)	51.34	Assumed to be the same as fossil propane
	HHV (MJ/L)	0.097	calculated
	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
	HHV (MJ/L)	25.31	calculated
	Density (kg/m^3)	493.00	Assumed to be the same as fossil propane
Renewable gasoline	HHV (MJ/kg)	46.31	CA-GREET3.0 model ("Fuel_Specs" tab)
	HHV (MJ/L)	34.62	calculated
	Density (kg/m^3)	747.61	CA-GREET3.0 model ("Fuel_Specs" tab)
Renewable naphtha	HHV (MJ/kg)	48.08	calculated
	HHV (MJ/L)	34.86	CA-GREET3.0 model ("Fuel_Specs" tab). Assumed to be the same as fossil naphtha
	Density (kg/m^3)	725.15	CA-GREET3.0 model ("Fuel_Specs" tab). Assumed to be the same as fossil naphtha
Renewable natural gas (gaseous)	HHV (MJ/kg)	54.03	Assumed to be the same as gaseous natural gas
	HHV (MJ/L)	0.038	Assumed to be the same as gaseous natural gas
	Density (kg/m^3)	0.7105	Assumed to be the same as gaseous natural gas

LCIF	Parameter	Value	Data source
Renewable natural gas (liquid)	HHV (MJ/kg)	55.21	Assumed to be the same as liquid natural gas
	HHV (MJ/L)	23.64	Assumed to be the same as liquid natural gas
	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)
	HHV (MJ/L)	0.013	calculated
	Density (kg/m^3)	0.0899	Hydrogen Tools. Basic Hydrogen Properties. Available at: https://h2tools.org/hyarc/hydrogen-data/basic-hydrogen-properties. Properties at 0 degrees C and 1 atm
Hydrogen (liquid)	HHV (MJ/kg)	141.80	CA-GREET3.0 model ("Fuel_Specs" tab)
	HHV (MJ/L)	10.04	calculated
	Density (kg/m^3)	70.8	CA-GREET3.0 model ("Fuel_Specs" tab)

Table 48: 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. https://doi.org/10.13031/2013.25421
	Corn oil	HHV (MJ/kg dry basis)	36.55	EPA (2018). Emission Factors for Greenhouse Gas Inventories. Available at: https://www.epa.gov/sites/default/files/2018-03/documents/emission-factors_mar_2018_0.pdf
	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. https://doi.org/10.13031/2013.25421
	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)
	Free fatty acids	HHV (MJ/kg dry basis)	42.21	GREET1_2022 ("Fuel_Specs" tab)

LCIF	Coproduct	Parameter	Value	Data source
	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)
	Light hydrocarbons	HHV (MJ/kg dry basis)	48.08	Assumed to be the same as renewable naphtha
		HHV (MJ/L)	34.86	
		Density (kg/m^3)	725.15	

Table 49: 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. Basic Hydrogen Properties. Available at: https://h2tools.org/hyarc/hydrogen-data/basic-hydrogen-properties. Properties at 0 degrees C) and 1 atm
Hydrogen (liquid)	70.8	CA-GREET3.0 model ("Fuel_Specs" tab)

Table 50: Supplemental parameters for other fuels

Type of fuel	Fuel	Parameter	Value	Data source
Fossil fuels	Aviation fuel	HHV (MJ/kg)	46.32	Calculated
		HHV (MJ/L)	37.4	Based on value from the NIR
		Density (kg/m^3)	807.4	Based on value from the NIR
	Coal (bituminous)	HHV (MJ/kg)	28.37	Based on value from the NIR
	Coal (lignite)	HHV (MJ/kg)	16.29	Based on value from the NIR
	Coal (sub-bituminous)	HHV (MJ/kg)	18.44	Based on value from the NIR
	Diesel	HHV (MJ/kg)	45.5	Developed by ECCC based on references used for the NIR
		HHV (MJ/L)	38.35	Calculated
		Density (kg/m3)	842.9	Based on value from the NIR
	Gasoline	HHV (MJ/kg)	45.8	Developed by ECCC based on references used for the NIR
		HHV (MJ/L)	33.45	Calculated
		Density (kg/m3)	730.4	Based on value from the NIR
	Heavy fuel oil	HHV (MJ/kg)	42.81	Calculated
		HHV (MJ/L)	42.5	Based on value from the NIR
		Density (kg/m3)	992.8	Based on value from the NIR
	Kerosene	HHV (MJ/kg)	46.67	Calculated
		HHV (MJ/L)	37.68	Based on value from the NIR
		Density (kg/m3)	807.4	Based on value from the NIR
	Light fuel oil	HHV (MJ/kg)	46.22	Calculated
		HHV (MJ/L)	38.8	Based on value from the NIR
		Density (kg/m3)	839.5	Based on value from the NIR
	Liquefied petroleum gas (LPG)	HHV (MJ/kg)	52.04	Calculated
		HHV (MJ/L)	26.41	Based on value from the NIR
		Density (kg/m3)	507.5	Based on value from the NIR
	Natural gas, gaseous	HHV (MJ/kg)	54.03	Calculated
		HHV (MJ/L)	0.038	CA-GREET3.0 model ("Fuel_Specs" tab)

Type of fuel	Fuel	Parameter	Value	Data source
		Density (kg/m3)	0.7105	Enbridge. Learn about natural gas-Chemical composition of natural gas. Available at: https://www.enbridgegas.com/about-enbridge-gas/learn-about-natural-gas. Properties at standard conditions.
	Natural gas, liquid	HHV (MJ/kg)	55.21	Calculated
		HHV (MJ/L)	23.64	CA-GREET3.0 model ("Fuel_Specs" tab)
		Density (kg/m3)	428.2	CA-GREET3.0 model ("Fuel_Specs" tab)
	Petcoke	HHV (MJ/kg)	36.24	Calculated
		HHV (MJ/L)	43.46	Based on value from the NIR
		Density (kg/m3)	1199.3	Based on value from the NIR
	Propane (gaseous)	HHV (MJ/kg)	51.34	Calculated
		HHV (MJ/L)	0.097	Calculated
		Density (kg/m3)	1.8839	CA-GREET3.0 model ("Fuel_Specs" tab)
	Propane (liquid)	HHV (MJ/kg)	51.34	Calculated
		HHV (MJ/L)	25.31	Based on value from the NIR
		Density (kg/m3)	493.0	Based on value from the NIR
	Stove oil	HHV (MJ/kg)	46.22	Assumed to be the same as light fuel oil
		HHV (MJ/L)	38.8	Assumed to be the same as light fuel oil
		Density (kg/m3)	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)	8.70	HHV for corn stover pellets. Value taken from: United States Environmental Protection Agency. (2016). Greenhouse Gas Inventory Guidance - Direct Emissions from Stationary Combustion Sources. EPA Centre for Corporate Climate Leadership.
	Wood chips from sawmill co-products	HHV (MJ/dry kg)	21.43	Density values for wood fibres are based on parameters from NRCAN's "Solid Biofuels Bulletin No. 2" (see Table 2). Available at: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/NRCAN_BB_no2_e_indd.pdf
	Wood pellets from sawmill co-products	HHV (MJ/dry kg)	21.43	Density values for wood fibres are based on parameters from NRCAN's "Solid Biofuels Bulletin No. 2" (see Table 2). Available at: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/NRCAN_BB_no2_e_indd.pdf