Methanol carbon footprint and certification

Guidance

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Disclaimer

This Guidance has been developed to accompany the studio Gear Up **Carbon footprint assessment tool for methanol production pathways, version 1.0 – May 2022.**

The Tool and Guidance have been developed for the International Methanol Producers and Consumers Association IMPCA.

studio Gear Up cannot guarantee the correctness of the results from this Tool, as they depend on non-verified, user-specified inputs.

Table of Contents

1 Introduction

1.1 Context of climate action in transport and industry

With increasing global attention for climate change in recent years, companies are stepping up on climate action, either to comply with tightening legislation or motivated by consumer preferences. Therefore, companies are increasingly reporting on the climate impacts of their activities, and on the carbon footprint of the products they produce and sell.

Methanol is a widespread platform chemical and precursor to many other products, such as plastics and cosmetics. Methanol is traditionally – and still mainly – produced from natural gas. With more than 95 billion litres produced worldwide, methanol is the world's most-shipped chemical commodity today.[1] The production and use of methanol cause about 165 Mtonne of climate emissions per year, or about 0.3% of all global climate emissions.[2]

Next to the use of methanol as a chemical, it can also be used as a liquid fuel in the marine and automotive sector, and it is seen as an emerging renewable energy resource. Whereas most of the methanol produced nowadays is still fossil-based, methanol can be also be produced from renewable sources as biomass or renewable electricity, or from waste streams such as municipal solid waste. Renewable methanol reduces greenhouse gas emissions up to 95% for CO_2 and up to 80% for NO_X.[1] Low-emission methanol could therefore play a large role in decarbonising certain sectors where options are currently limited – particularly as a feedstock in the chemical industry or as a fuel in road or marine transport.[1] In the shipping sector, the methanol could replace fossil-based heavy fuel oil.

This connects methanol to climate action via two sides: on the one hand a large and currently fossil oriented industry will have to reduce climate emissions, while on the other hand, methanol from renewable feedstock attracts attention as a renewable fuel. Therefore, global methanol stakeholders, represented by the International Methanol Producers and Consumers Association (IMPCA), recognise that the climate impact of methanol produced from various feedstocks needs to be better understood.

1.2 Product carbon footprint of methanol

The environmental performance of products is often assessed by calculating the product carbon footprint. A product carbon footprint analysis considers all the greenhouse gas emissions from all the activities involved: all the way from the production and/or collection of feedstocks, via conversion and transportation steps, to the end-of-life fate of the product. This is done by a lifecycle assessment-based approach, as is further explained in Section 2.

The approach in this Guidance is based on the methodology published by the International Sustainability & Carbon Certification (ISCC EU)[3], which in turn is in line with the biofuel carbon footprint methodology of the Renewable Energy Directive (RED II).[4] The ISCC methodology is intended and well-suited for the assessment of the product carbon footprint of biofuels, but it is also suitable (with some small alterations) for calculating the product carbon footprint of fuels *and* materials from a wider range of feedstock. The RED/ISCC methodology provides a strict ruleset and procedure, so that calculations are reproducible, and non-disputable. In this way, the ISCC methodology is an international, practical and

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[1] Methanol Institute 2018, Renewable Methanol Report.

[2] Methanol from natural gas has a lifecycle carbon footprint of about 2.2 kg CO_2eq/kg methanol. Total global greenhouse gas emissions in 2020 amount to about 60 gigaton CO_2eq [UNEP 2021, Emissions Gap Report].

[3] ISCC EU 205 – Greenhouse Gas Emissions (v4.0, 1 July 2021).

[4] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. In July 2021, the European Commission proposed changes to this Directive, which are expected to be formalised (after approval of Parliament and Council) in 2022.

transparent methodology, suitable for including product carbon footprints in a trade specification.[5, 6]

The greenhouse gas performance of methanol depends strongly on the type of feedstock, on conversion efficiencies and on energy use during the production process. Some production pathways have been assessed in the past.

The RED II and the GREET Model[7] provide default values for methanol and other fuels from different feedstocks. These default values reflect generic methanol supply chains with generic conversion processes and are therefore useful mainly to obtain a generic impression of the performance of those fuels. Default values for renewable methanol in the RED II reflect conservative values on purpose, so to motivate suppliers to present real (and certified) values.[8] The underlying data for sustainability calculations is typically thin and sometimes up to 25 years old.[9]

For reference, the default values in the GREET Model and the RED II are shown in Figure 1 for different feedstock sources. Methanol produced from coal (GREET: 158.2 g CO_2eq/MJ:) and natural gas (GREET: 93.2 g CO_2eq/MJ and RED: 97.1 g CO_2eq/MJ) generally results in a high emission. Methanol from biomass or black liquor typically has a very low emission.
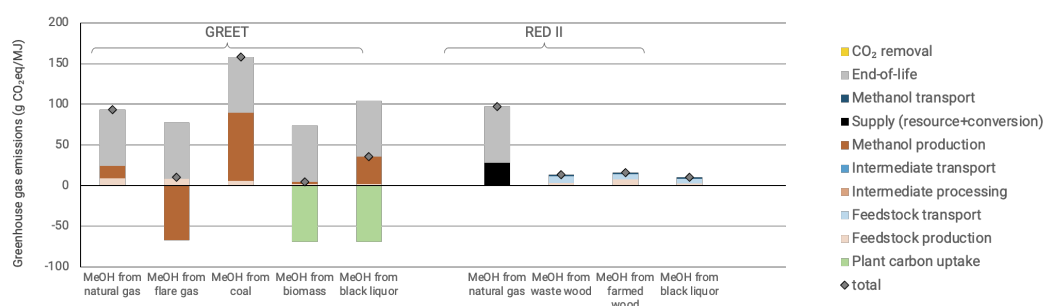

Figure 1: Default values for methanol sustainability performance from different feedstocks, from GREET Model and RED II. Note that there are negative emissions shown in the graph.[10] The combined results are shown with diamonds.

Conservative default values should only be used if supply chain certification is not feasible or viable. To provide methanol consumers in the chemical industry and transport sector with a more precise insight in the carbon footprint requires that stakeholders along the supply chain use a single calculation methodology. In this Guidance, therefore, a harmonised methodology and guidance is given to calculate the product carbon footprint as described in the EU-RED and ISCC.

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[5] The ISCC methodology covers all sustainable feedstocks including agricultural and forestry biomass, biogenic waste and residues, non-biological renewable materials and recycled carbon-based materials.

[6] ISCC EU 102 – Governance.

[7] The GREET Model refers to Greenhouse Regulated Emissions and Energy use in Technologies Model (GREET Model). This model is a carbon footprint methodology as explained in this Guidance in Section 2.2.

[8] For methanol, the RED II only contains default values for methanol from waste wood, from farmed wood and from black liquor. Underlying literature also contains a value for methanol from natural gas [EC JRC 2017 Definition of input data to assess GHG default emissions from biofuels in EU legislation].

[9] Most of the underlying data stems from the 1990s [EC JRC 2017 Definition of input data to assess GHG default emissions from biofuels in EU legislation].

[10] In the case of methanol produced from flare gas, GREET assumes this avoids otherwise unavoidable carbon emissions. This is (currently) not an option in the RED II methodology. Where methanol is produced from biomass, GREET displays both the carbon uptake during the growth of the biomass and the carbon emission at the end. Note that in the RED II methodology, CO_2 uptake and final emission are assumed to cancel out and therefore are not shown.

1.3   Technical product standard and carbon footprint of methanol

Methanol is often traded according to IMPCA references specification. This is a standard for technical aspects of the methanol, and it involves limits and tests methods for parameters such as the purity of the methanol and the concentration of substances as chloride, sulphur, and acetone. This technical standard is based on regulated tests and protocols, thereby assuring the technical quality of the methanol.[11]

In contrast to the determined technical standard of methanol, which can be measured at a single point (a moment of handing-over between seller and buyer), the carbon footprint at such a point is the result of all steps upstream in the supply chain. Moreover, the technical standard should be exactly met. Boundary values should not be exceeded. For the carbon footprint, consumers may set their own requirements. The specification would only contain the "measurement method" and not any limits.

The calculation of the carbon footprint requires insight in the upstream production of feedstock and in the performance of the conversion process. This may be achieved in two ways:

The full supply chain is considered and data is collected along the supply chain. This data is processed in one complete analysis of the fully supply chain. This calculation can only be done when the full supply chain is known. It is currently the most common option.

For each step in the supply chain, the emissions and savings resulting from that step are calculated, and added on top of emissions known from the feedstock entering that step. This requires that every stakeholder along the supply chain uses the same methodology for calculating the greenhouse gas intensity of the products they sell as feedstock to the next step.

The Tool currently assumes the first method.

1.4   Reader guidance

Chapter 2 of this Guidance explains the methodology and underlying topics of carbon footprint analysis. This includes a detailed explanation and description of the lifecycle assessment methodology and elaborates on the calculations which are the basis of the developed methanol footprint Tool.

Chapter 3 provides a guidance of the developed Tool to calculate the methanol footprint.

In Chapter 4 provides guidance on the actual certification of carbon footprints, with an overview of main certification schemes, details of the ISCC certification scheme, and guidance on how companies can prepare for ISCC certification, thereby linking this information to the developed methanol Tool.

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[11] IMPCA Methanol Reference Specifications. Version 9, 10 June 2021.

2 Carbon footprint analysis

2.1 Introduction to lifecycle assessment and carbon footprint analysis

What is a carbon footprint analysis?

A carbon footprint is the total climate impact of a product or an activity. A product carbon footprint considers all greenhouse gas emissions from all the activities involved with i) the production or collection of feedstocks, ii) the transport of feedstock, intermediates, and final products, iii) the conversion into intermediate, and final products and iv) the end-of-life fate of the final product (combustion in case of an energy product). In case of application in transport, this inclusion of all lifecycle steps is often called well-to-wheel (in a vehicle), well-to-wake (in a ship). In case of a material application, it is called cradle-to-grave.
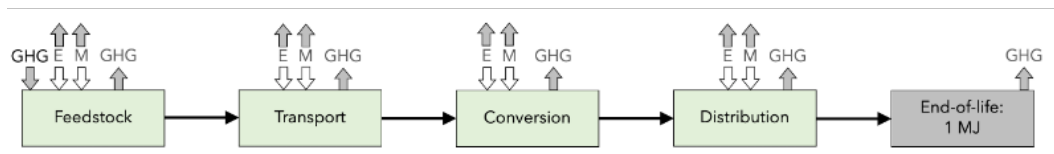

Figure 2: Inventory of complete lifecycle of methanol. GHG = Greenhouse gases with mainly CO_2, CH_4 and N_2O, M = Materials, E = Energy.

The carbon footprint is only one category of a lifecycle assessment (LCA). An LCA considers many environmental impact categories (for instance including ozone layer depletion, freshwater eutrophication, pollution etcetera[12]) and tries to give a composite view of the environmental burdens, while the carbon footprint includes only one impact category, which is the global warming potential (GWP).

With increasing interest of companies to report on the climate impacts of their activities, carbon footprints of the products they produce become more and more important. In case a company produces multiple products, a company's carbon footprint (or corporate carbon footprint, CCF) includes all the separate product carbon footprints and the direct and indirect emissions from a company.[13]

Use of LCA principles

In the carbon footprint, all major greenhouse gasses are accounted for, which mainly concern carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The weight of these gasses is expressed in CO_2-equivalent units, known as Global Warming Potential (GWP), with CO_2 having, by definition, a GWP of 1. The GWP of methane and nitrous oxide is based on their radiative efficiency and their lifetime in the atmosphere. The RED II applies the following GWPs, given in Table 1.[14]

Table 1: Used Global Warming Potentials (GWP) compliant with RED II.

Greenhouse gas	GWP
CO_2	1
CH_4	25
N_2O	298

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[12] ISO 14040:2006. Environmental management – Life cycle assessment – Principles and Framework.

[13] Leivas, R., Laso, J., Hoehn, D., Margallo, M., Fullana-i-Palmer, P., & Aldaco, R. (2019). Product vs Corporate Carbon Footprint: A Case Study for the Spirit Drinks Sectors. CHEMICAL ENGINEERING, 76.

[14] Other carbon footprint methodologies may apply different GWPs.

For each step in the supply chain of methanol (as shown in Figure 2), it is determined how much feedstock, intermediate or final material passes through, to deliver a unit of methanol at the end (in this example: to deliver 1 MJ of methanol to the consumer). Then it is determined how much greenhouse gas emissions result in each step, both directly from the activity as well as from the production of the energy and materials consumed in that step. For these "consumables", often, standard emission values are taken from databases and literature to give estimates when actual values are not available. At the last step of the lifecycle, the end-use, it is determined if there are end-of-life emissions (see Section 2.2.2). Capital goods, such as the construction of a factory building, and related emissions, are not accounted for in a carbon footprint.

The carbon footprint is expressed in grammes of CO_2 equivalent emission per unit of product delivered, thus for example for methanol as a fuel expressed as g CO_2eq/kg or g CO_2eq/MJ. When the carbon footprint is expressed per unit of MJ, the energy is expressed as Lower Heating Value (LHV) in this Guidance.

During the lifecycle, co-products could be produced, as for example the occurrence of a co-product as steam or wastewater during conversion of methanol to a fuel or a product. In the RED II / ISCC approach, the carbon footprint is distributed over the products in such a way that each product has the same impact per energy unit.

2.2 (Product) carbon footprint methodology

There are several carbon footprint methodologies with different quantification approaches. All carbon footprint methodologies used globally follow principles set out by ISO- standards 14044 and ISO 14040. These standards are very general and leave several choices open, especially regarding dealing with multiple intermediate or end-products. With variations on the ISO standards, one could come to very different outcomes for the same supply chain or conversion pathway.

A well-known methodology to assess the product carbon footprint of all biomass-derived fuels or materials in the European market, is the RED methodology.[15] The method is also useable with some adjustments to calculate the impact of fuels and energy products produced from other feedstock, including non-renewable feedstock. Other carbon footprint methodologies or protocols for sustainability reporting are the Greenhouse Regulated Emissions and Energy use in Technologies Model (GREET Model), the Emission Trading Scheme (ETS) and the Greenhouse Gas Protocol.

- **RED II**: In the RED, the product carbon footprint is called the greenhouse gas impact. A key aspect of the RED methodology is that it treats co-products via energy allocation. This means that at a point where multiple products are being produced, all the emissions up to that point are divided equally over the energy content of all products at that point.[11]

- **GREET:** Currently, GREET includes the calculation of methanol produced from natural gas, biomass, and coal. It does not currently include the production of methanol from (renewable) electricity, options related to utilising or selling CO_2, or to combine multiple feedstocks or technology pathways in a single facility. The GREET model is therefore not flexible to calculate other pathways and feedstocks.
  The main difference between GREET and RED II resides in the treating of the co-products. RED II is based on the principle that all co-products carry a responsibility for the supply chain and climate impacts are equally distributed over the total energy output. GREET is based on the principle that co-products avoid a production process elsewhere, and the emissions that such a process would have caused may be subtracted from the main product. Both approaches to co-products are valid but require different information and will give different outcomes. GREET requires a deeper understanding of co-products

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[15] Annex V part C of the Renewable Energy Directive describes the rules for the calculation of the greenhouse gas emissions. As the ISCC follows the RED methodology, the calculation methodology and accompanying formulas will be explained in this report (Section 2.2.1)

which is often not available and is subject to changes over time and geographically. RED II gives more consistent results and is generally easier to apply.

- **ETS:** The ETS is based on emissions trading by a market-based approach for reducing emissions of greenhouse gasses. The ETS puts a price to greenhouse gas emissions emitted from certain sectors. It focusses only on fossil emissions, as renewable fuels count as zero, and is direct emissions only. For now, the aviation and power sector, and the manufacturing industry are included in the ETS. In the new proposed ETS, as part of the Fit-for-55 climate package[16],international maritime and road and buildings will be included.

- **Greenhouse Gas Protocol:** The Greenhouse Gas Protocol is a globally recognised organisation for measurement and management of greenhouse gasses in the public and private sector. The protocol provides standards at various organisation levels including corporate standards and product standards.
  The protocol furthermore defines direct and indirect emissions. Direct emissions are emissions from sources that are controlled or owned by the reporting entity, and indirect emissions are emissions due to the reporting entity's activities but are controlled by other parties. Lastly, the protocol divides the emissions in three scopes, namely scope 1, 2 and 3. The differences between these scopes related to a company or a product carbon footprint are explained in Table 2.

Table 2: Overview of different scopes, defined in the Greenhouse Gas Protocol, specified for product carbon footprint and company carbon footprint.

Type of footprint	Scope 1	Scope 2	Scope 3
Product carbon footprint	Direct CO_2eq emissions from the methanol production process	CO_2eq emissions from electricity, heat and cooling directly related to methanol production	Cradle-to-gate CO_2eq emissions from all inputs required to produce methanol, and emissions from transport and distribution, and end-of-life of the methanol product.
Company carbon footprint	Direct CO_2eq emissions on the premises of the company, include methanol process but also company vehicles.	CO_2eq emissions from electricity, heat and cooling used in company, may include heating the office spaces and the canteen.	Downstream and upstream CO_2eq emissions from the company's operations, may include employee commuting.

2.2.1 ISCC carbon footprint certification

The ISCC is the leading certifying body in carbon footprints in the European market. The ISCC operates under different certification systems for different markets. These systems are ISCC EU, ISCC PLUS and ISCC CORSIA:

- ISCC EU is a certification system to demonstrate sustainability requirements and follows the requirements and the methodology of the RED 2018/2001/EC (often referred to as RED II). ISCC EU has been recognised by the European Commission since 2011. The ISCC EU methodology is intended and well-suited for the assessment of the product carbon footprint of biofuels, but it is also suitable (with some small alterations) for calculating the product carbon footprint of fuels *and* materials from a wider range of feedstock. The ISCC system provides solutions for the implementation and certification of sustainable supply chains of agricultural and forestry raw materials, waste and residue raw materials, renewable materials of non-biological origin and recycled materials and fuels.

- ISCC PLUS is a voluntary certification system for all markets and sectors not regulated by the RED II, such as food, feed, or biofuel markets outside the EU and bioenergy, and for

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[16] The Fit-for-55 package consists of various legislative proposals and together they serve to fulfil the legal obligation of the EU to achieve at least a 55% net reduction in greenhouse gas emissions by 2030 compared to 1990. This package is currently under revision at the European Commission.

diverse industrial applications as plastics or packaging. ISCC PLUS deals with these additional sectors that are mentioned, and is therefore only partially compliant with the RED II. Under ISCC PLUS, all types of agricultural and forestry raw materials, waste and residues, non-bio renewables and recycled carbon materials and fuels are covered that contribute to the biobased or circular economy. The ISCC PLUS covers the same certification requirements as the ISCC EU but is customised to meet the needs of different markets or specific applications. This expansion to other markets and end-products means adjustments in the carbon footprint methodology. For example, if methanol is derived and used for a (chemical) product, it means that there are no end-of-life emissions because the product is not combusted. These adjustments and implications will be further specified in Section 2.2.2.

- ISCC CORSIA (PLUS) is a certification system for sustainable aviation fuels demonstrating compliance with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). In this Guidance, this certification system is not explained in detail.

The carbon footprint methodology of the ISCC EU and ISCC PLUS is explained in Section 2.2.1.

2.2.2 Carbon footprint calculation based on ISCC methodology

The carbon footprint of the methanol lifecycle calculated in the RED II or ISCC methodology is the sum of the greenhouse gas emissions emitted during feedstock production, transport and distribution, conversion, and at end-of-life, minus savings related to agricultural management and CO_2-capture and storage or replacement.

The ISCC methodology assigns these emissions and savings to certain parameters, given in Figure 3, with each of them occurring at a certain step in the methanol lifecycle. Whereas the formula and approach used by ISCC is intentionally designed for biofuels, it can also be used to calculate the carbon footprint for methanol from multiple types of fossil feedstocks, and for the use of materials derived from methanol as well.
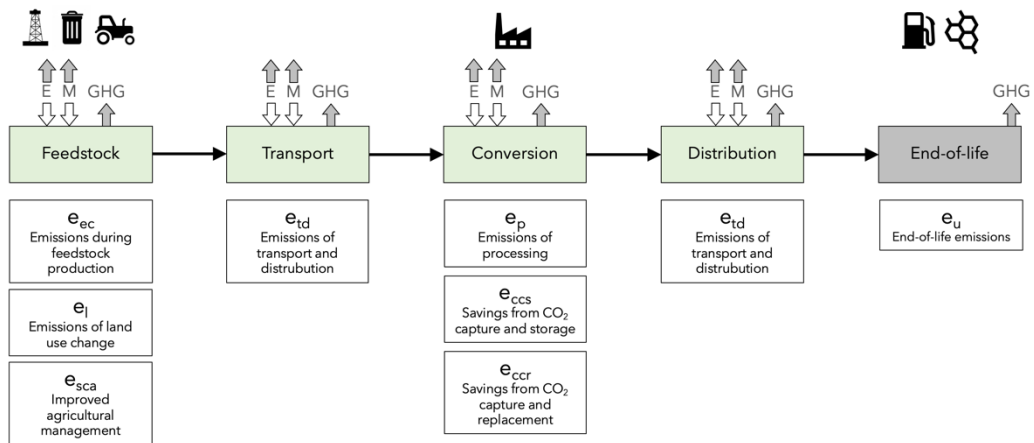
Figure 3: Overview of supply chain and relevant parameters for each supply chain element. Note that not all parameters are relevant for each pathway. GHG = Greenhouse gases (mainly CO_2, CH_4 and N_2O), M = Materials, E = Energy. Note that the names of some parameters in this Figure are not identically as given in the ISCC methodology, as the formula is adjusted to multiple types of (fossil) feedstocks, and for the use of materials derived from methanol as well.

Depending on whether the feedstock is fossil or renewable, an on whether methanol is used as a material or a fuel, the emissions at the beginning and the end of the supply chain are represented differently. This is discussed below in the section on End-of-life emissions.

The different parameters presented in Figure 3 are further explained below.

Emissions during feedstock production (e_ec) and overview of pathways
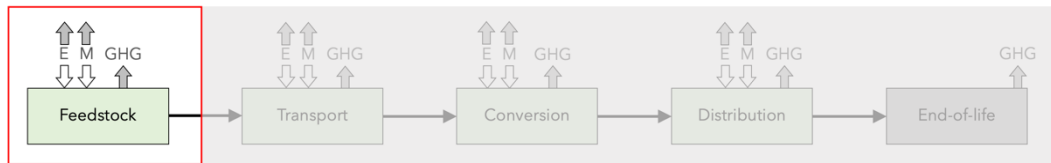
Methanol is traditionally – and still mainly – produced from natural gas but can also be produced from other feedstocks. Also, a mixture of a renewable and fossil feedstock to produce methanol is also possible. In this Guidance, we explain the carbon footprint approach for the following feedstocks:
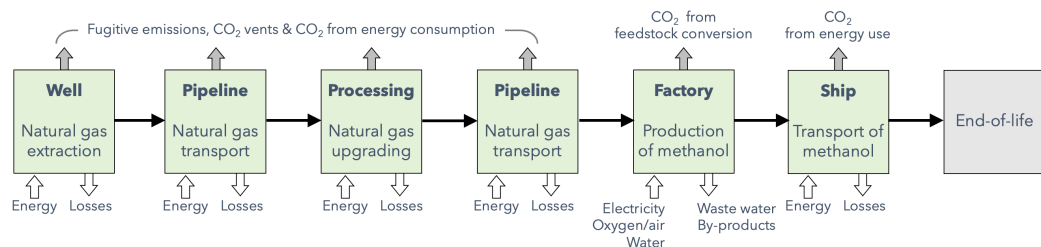
- Fossil methanol: from natural gas and coal
- Bio-methanol: from biomethane from anaerobic digestion
- Bio-methanol: from solid biomass
- Bio-methanol: from (the biogenic part of) municipal solid waste
- E-methanol: from captured CO2 and electricity

Fossil feedstock: Natural gas and coal

Natural gas is extracted from wells, upgraded, and transported via the gas grid. This natural gas production and transportation leads to emissions related to the energy needed for the extraction, and methane emissions at source. Methane, and carbon dioxide, is released when natural gas is flared or vented. Methane is also released in small leaks, called fugitive emissions, from valves and other equipment used in drilling and production.

The emissions of natural gas production can vary depending on the natural gas quality and specifications. Specifications as the density, the lower heating value (LHV), the carbon content and consequently the end-of-life-emissions affect the natural gas production emissions. Data on CH_4 leakage, venting and flaring, CO_2 venting, and other losses is included in Appendix A.1.1.

Carbon emissions from using coal to produce methanol result from coal mining, selection and washing, and transportation of the coal. The carbon emissions from mining concern coalbed carbon leaks and emissions from energy use. During mining and coal selection, (grid) electricity is used. During coal selection, spontaneous combustion can (rarely) occur. Data related to climate emissions during coal production is included in Appendix A.1.2.

Biomethane from anaerobic digestion
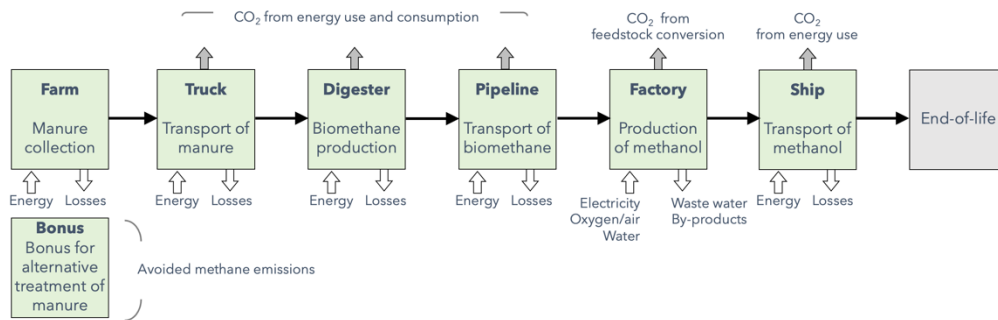
At farms, various feedstocks as cow or pig manure, or maize silage, are collected which are transported to an anaerobic digestion facility. Most anaerobic digestion facilities use a variety of feedstock to strike an economic balance between emission reduction (best with waste streams and manure) and biogas output (highest with crops). At the digestion facility biogas and some digestate is produced. The biogas is then upgraded to biomethane. During this upgrading, the biogas is cleaned, and the methane is separated from the carbon dioxide and other gasses and components. The produced biomethane, which contains close to 100% methane, has now natural gas quality and can be injected into the grid. The biomethane is transported via the gas grid to a methanol production facility.

The digestion of cow or pig manure avoids emissions that would not have taken place during alternative manure treatment (or no treatment). The RED therefore awards a bonus for the processing of manure of 45 g CO_2eq/MJ manure or 54 g CO_2eq/kg fresh manure.[17] Because of the bonus for avoided emissions of methane, biomethane from manure often has a negative carbon footprint. Biomethane-based methanol therefore often avoids >100% emissions in comparison with fossil fuel comparators.

When a crop, like corn, is used for biomethane production, the greenhouse gas emissions from feedstock production, due to use of fertilizer, diesel use etcetera, are considered.

During multiple stages in the production of biomethane and subsequent biomethanol, greenhouse gasses are emitted. Collection and transport (by truck) of the manure usually leads to some emissions. These emissions are discussed in parameter e_{td}. Emissions of the transport of biomethane are also discussed in this parameter. Upgrading of the biogas to biomethane requires energy, which may lead to emissions if fossil energy is used. This is further specified in emissions from processing (e_p).

Biomethane yield and avoided methane emissions from the production of cow manure, pig manure, organic waste and maize silage are included in Appendix A.1.3.

Solid biomass
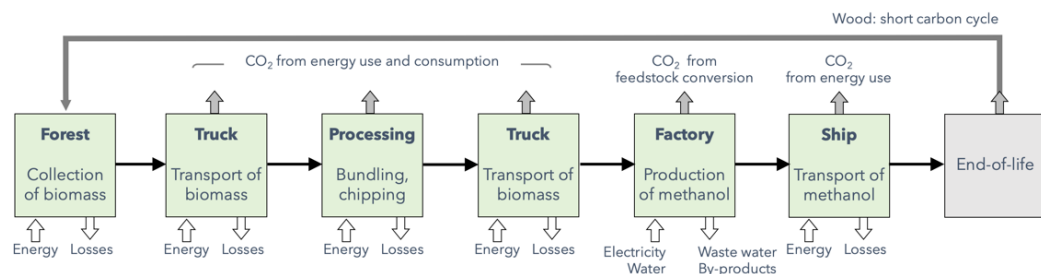
Methanol from solid biomass can be made from wood and forestry residues or other types of biomass. Biomass has a relatively short carbon cycle. This means that the CO_2 emissions during combustion is equal to the CO_2 uptake during the growth of the biomass and therefore

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[17] The calorific value varies between source (animal, location). Therefore, the 54 g/kg fresh manure can be too high or too low. It would be better to calculate with the 45 g CO_2eq/MJ manure, but the calorific value is often unknown.

they cancel out and biomass can be considered as climate neutral.[18] Depending on the type of biomass, the system size, the landscape and management practices, the carbon balance can be settled within few years.

Collection of solid biomass usually leads to some emissions. These emissions are small and usually ignored in lifecycle assessment. Emissions of the transport of biomass to the factory are discussed in parameter e_{td} (emissions from transport and distribution). Next to this, there are small emissions from processing of the solid biomass because of the bundling or chipping. These emissions are discussed in parameter e_p (emissions of processing).

If a waste or a (wood/forestry) residue is used as a feedstock, any upstream emissions are allocated to main products or previous functions. Greenhouse gas emissions of extraction, production or cultivation of these residues and waste streams therefore count as zero.

If a purpose grown feedstock, like a tree, grass or agricultural crop, would be used to produce methanol, the greenhouse gas emissions resulting from the cultivation process should be considered. This includes emissions from sowing, fertiliser production and fertilizer application, harvesting, drying and storage of the biomass.[19]

Data about the carbon and moisture content of the biomass and assumed losses during transport are included in Appendix A.1.4.

Municipal solid waste (MSW)
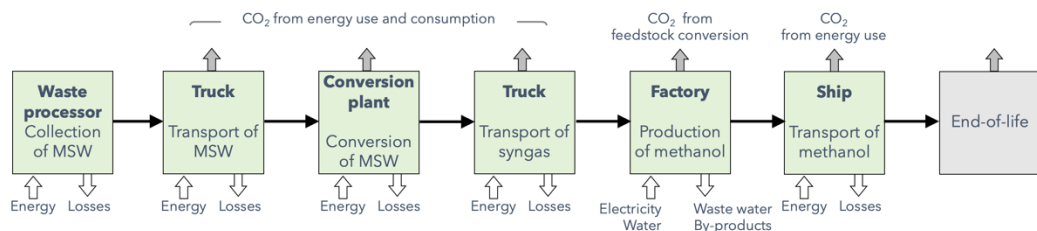
Municipal solid waste (MSW), commonly known as trash or garbage, consists of the everyday items we use and throw away. Generally, 50 to 60% of MSW (paper, glass, plastics, and metals) could be recycled, and 40-50% of MSW could be used to produce fuel or other forms of energy.[20]

MSW can be converted into liquid and gaseous biofuels for production of heat and power or be used as a transport fuel. Typically, management of domestic wastes involves separation at source into: [21]

- Recyclable materials (metals, paper, and plastics): Used for manufacture of recycled products;
- Biogenic fraction (food waste): May be converted to biogas and biomethane via anaerobic digestion;
- Non-biogenic fraction (shredded textiles, plastics): Can be combusted or converted to syngas and may lead to a recycled carbon fuel.[22]

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[18] Where methanol is produced from biomass, GREET displays both the carbon uptake during the growth of the biomass and the carbon emission at the end. Note that in the RED II methodology, CO_2 uptake and final emission are not shown because they cancel out.

[19] In Section 4.3 of the ISCC methodology, the methodology to calculate these different elements, as well as information about data gathering, is explained in detail.

[20] AlMohamadi 2021, Production of gasoline from municipal solid waste via steam gasification, methanol synthesis, and Methanol-to-Gasoline technologies: a techno-economic assessment. AIMS Energy 9(1): 50-67.

[21] ETIP Bioenergy: MSW as a feedstock for biofuels production: Overview (website).

[22] 'Recycled carbon fuels' means liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations.

The carbon footprint of methanol from MSW depends on the fraction of biogenic waste, and on the judgement of the (recyclability) of the nonorganic part of the waste.[23] High fractions of biogenic waste and of (otherwise) non-recyclable material leads to a low carbon footprint and high savings. If the non-biogenic share contains recyclable material, it may not be considered as a waste. The carbon emissions, from the process and final product together, would then (partly) cause a climate impact.

Transport of the MSW to the conversion plant and transport of the syngas usually leads to some emissions. These emissions are discussed in parameter e_{td} (emissions of transport and distribution).

Data about the carbon and moisture content of the MSW and assumed losses during transport are included in Appendix A.1.5.

Captured CO_2 and (renewable) electricity
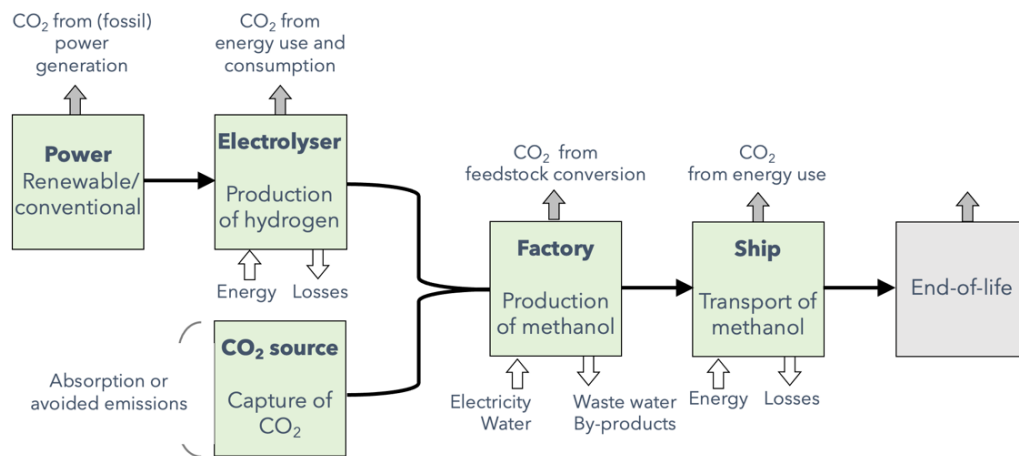
E-methanol is produced by combining (green) hydrogen, on basis of electrolysis using (renewable) electricity, with an external source of carbon dioxide.

Production of hydrogen by electrolyser: Electrolysers convert water into oxygen and hydrogen. Electrolysers require demineralised water of high purity. Conventional process water contains traces of minerals that are ionic and would be influenced by the electric current, thereby reducing the efficiency of the electrolyser. With current industrial-scale technologies technologies, electrolysers achieve energy efficiencies of about 66% on a lower heating value (LHV) basis.

(Renewable) electricity: The used electricity can either be renewable (solar PV, wind sourced electricity) or grey (from the grid). Emission factors for national grid electricity differ for each country. In Appendix A.3, default values for solar PV, wind sourced electricity and the carbon intensity of the grid electricity from Europe and USA are added.

Carbon dioxide (CO_2): The carbon dioxide is assumed to originate from the captured and unavoidable emissions from another industrial process. The CO_2 can be biogenic or fossil, which impacts the process and end-of-life emissions, or direct air capture. It is important whether the capture credit of the CO_2 has already been taken or not. Only fossil, captured CO_2 whose credit has not yet been taken can count as zero emission (see parameter eu – End-of-life-emissions). It is assumed that the CO_2 is provided from an industrial source "across the fence" and does not include any feedstock transportation.

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[23] In the frame of the RED, methanol from non-recyclable waste count as a Recycled Carbon Fuel (RCF). The RED Directive explicitly states that feedstock for RCFs should not be suitable for material recovery. Proof of this will have to be provided through certification. Note that the definition of the waste part in MSW may change in the coming years, as the obligatory share of recycling is increasing – that part will maybe be available for RCF.

Data about the carbon footprint of demineralised water, and default values for different electricity (renewable) sources are given in Appendix A.3 and A.4.

Emissions as a result of carbon stock changes caused by land-use change (e_l)
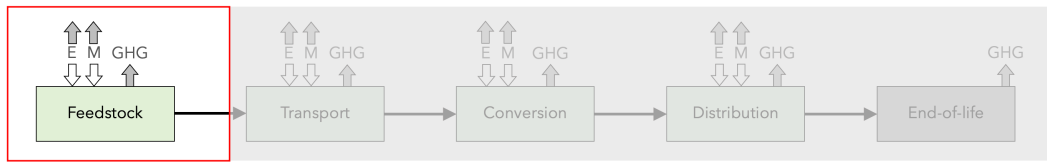
Please note that this parameter is only relevant if methanol is produced from biomass and if this biomass is not considered to be a residue.

Land-use change is a change from one of the following IPCC land cover categories: forest land, grassland, wetlands, settlements, or other land, to cropland or perennial cropland. When a land-use change occurs for the supply of feedstock, this impacts the carbon stock in that land.

The change in carbon stock can be calculated by subtracting the actual land use from the carbon stock of the reference land use (prior to the land-use change). The carbon stocks of the actual and reference land, annualised over 20 years, depend on the soil organic carbon and the carbon of the vegetation. The result is divided by the yield of the raw material (dry matter).

The RED II provides a bonus if degraded land is restored to produce biomass. This bonus of 29 g CO_2eq/MJ can be applied if can be proven that the land was not in use for agriculture or any activity (in January 2008), and that the land is severely degraded. The latter means that the land is, for a long period, significantly salinated, there is a significant low organic matter content or has been severely eroded. The bonus is applied for a period of 20 years from the date of conversion of the land.

In the model, for the supply chains involving biomass, indirect land use change is not included. Indirect land use change happens when an existing cropland is being used, and this land is no longer available for the original function. The original function (crop) may be supplemented by others elsewhere, and this may cause a loss of natural land elsewhere which may cause carbon impacts. However, indirect emissions cannot be included in the current Guidance since they cannot be observed or measured for individual supply chains.

Emissions from processing (e_p)
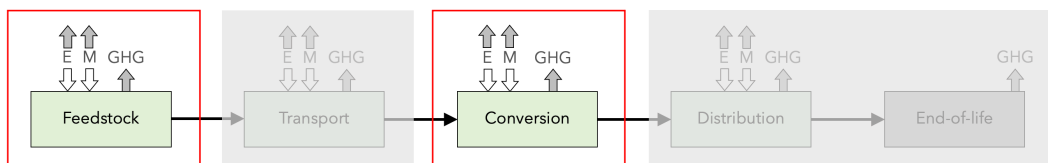
Emissions from processing (e_p) can occur during feedstock processing (depending on the type of feedstock) and during conversion of the feedstock to methanol (depending on the pathway).

Conversion of the feedstock to methanol leads to process emissions. With mass and energy balances of the installation, these process CO_2-emissions can be calculated. This requires an understanding of the inputs and products from the conversion facility. For all feedstock and products, the amount of carbon is calculated. Each tonne of C delivers $^{44}/_{12}$ tonne of CO_2. The amount of carbon can be calculated with the fraction of C in methanol ($^{12}/_{32}$). The difference between input and output, i.e. the balance of carbon, is assumed to leave the installation as CO_2 process emissions.[24]

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[24] CO_2 emissions mainly reside in stack emissions, and process condensates that are locally combusted for energy recovery purposes, while a relatively smaller volume occurs from wastewater treatment.

For fossil methanol (natural gas and coal), the exact carbon balance over the installation depends on the carbon content of the natural gas/coal feedstock. For instance, Northwest European gas has a carbon content of 63%, whereas Canadian gas has a carbon content of about 70%. A lower carbon content may increase the carbon emissions in from the installation. A lower carbon content may be an indication for higher amounts of CO_2 impurities, which would lead to higher emissions in the upgrading facilities. The average carbon efficiency (carbon in methanol output / carbon in natural gas input) is 78% in a range from 72% to 84%.

In Annex A.1, a carbon balance example is given out for each default pathway.

Emissions of transport and distribution (e_{td})
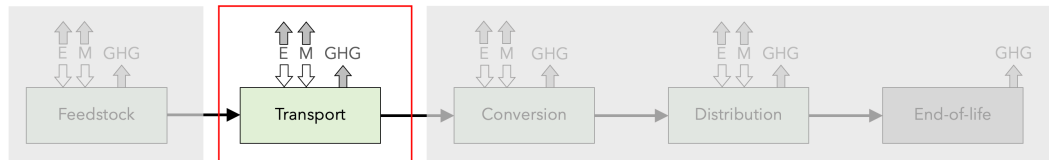
Emissions because of transport and distribution are the sum of all transport emissions in the lifecycle of methanol (-derived products). These emissions vary from emissions during feedstock transport (e.g. transport of biomass or transmission of natural gas in the grid) to emissions of the end-product to the end-user (e.g. methanol from the conversion facility to a ship owner).

Different transport modes as trucks on diesel, trains or ships have different emission factors. These emission factors are added in Appendix A.2.

End-of-life emissions (e_u)

If end-of-life emissions are emitted and need to be considered in the carbon footprint depend on the end-use and on the feedstock type.

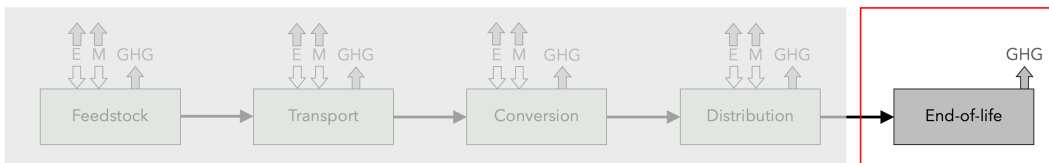**Methanol as fuel:** If methanol is used as a fuel, and derived from a fossil resource, this will result in end-of-life CO_2-emissions due to combustion of for example natural gas or coal. For emissions at end-of-life, this equals one molecule of carbon dioxide from each molecule of methanol, which is $^{44}/_{32}$ g CO_2 per g methanol, or 69 g CO_2/MJ.

For methanol based on renewable sources, such as biomass or the organic fraction of waste, the end-use emissions are climate neutral. The carbon was previously absorbed from the atmosphere during plant growth. Therefore, CO_2 resulting from the combustion of renewable methanol does not result in additional CO_2 within the atmosphere. When carbon is sourced from direct air capture, this is also the case. When carbon is captured from another process this avoided an earlier (and otherwise unavoidable) emission to the atmosphere. The carbon emission from the end-use of methanol thus rather represents a delayed emission and since it would have taken place anyway in absence of the carbon capture, it is therefore considered to be net climate neutral.[25,26]

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[25] In this case, the emitter does not receive any credit for the carbon capture. If the emitter already receives a credit, this means that the end-of-life emissions of this CO_2 are stoichiometric. The tool includes an option to split the capture credit, e.g. it is possible to count the captured CO_2 as 50% fossil and 50% already-accounted-for-CO_2.

[26] Note that this "credit" can only be taken once. For instance, if CO_2 is captured from a steel mill, and this steel mill does not claim that this activity decreases the steel carbon footprint, then then the carbon becomes climate neutral and it may be used to decrease a methanol carbon footprint. However, if CO_2 is captured from
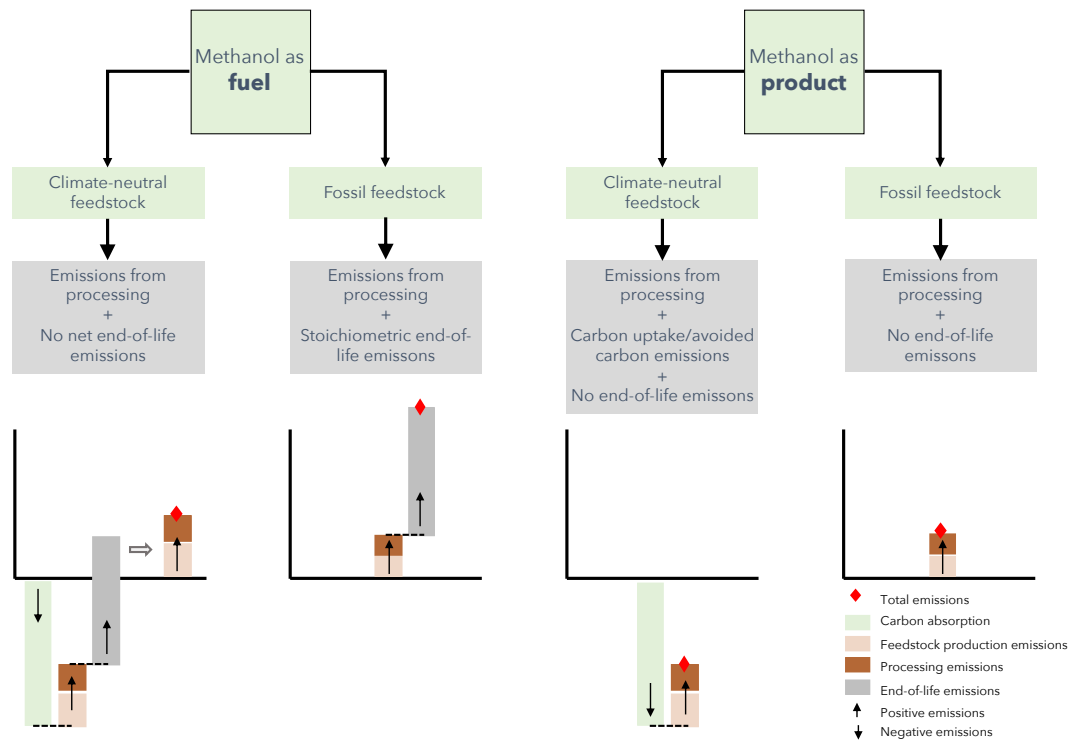
Figure 4. Four different presentations of carbon uptake at the source and end-of-life emissions, depending on the fate of methanol as a material or a fuel, and on the feedstock being fossil or renewable.

When MSW is used as a feedstock, emissions may be partly climate neutral, when they stem from the biogenic part of the waste, or if they stem from the non-recyclable carbon. The part that stems from the recyclable carbon in the feedstock has a climate impact, and end-of-life emissions.

Methanol used for a (chemical) product: If methanol is derived and used for a (chemical) product, it means that there are no end-of-life emissions as the product is not combusted. However, when discarding the product, and a fossil feedstock has been used, fossil emissions will still take place at end-of-life.

If a renewable feedstock is used, carbon is absorbed from the atmosphere (during growth of crops), or emissions are avoided (for example at e-methanol or the use of waste), which is an advantage over fossil feedstock.

In the case of methanol from MSW, the carbon footprint and end-of-life emissions differ depending on the composition of the MSW. Figure 5 shows carbon footprint of methanol from MSW with varying fossil contents. If all carbon in the MSW is of biogenic origin, or if the non-biogenic share is considered to be climate neutral, then there are no end-of-life emission and total emissions are the result of emissions from transport and intermediate processing only (10 g CO_2eq/MJ, MSW0 case). The limited emissions of the methanol production are, in this example, the result from the consumption of natural gas (as defined in the natural gas pathway) and electricity (wind power). If, however, the non-biogenic share contains recyclable material, then it may not be considered a waste. The carbon emissions, from the process and final product together will then (partly) cause a climate impact and end-of-life emissions. The figure shows that the emissions from end-use increase when moving to 10%, 25% or 50% non-climate neutral carbon in the MSW.

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an ethanol production facility and this aspect is already used to decrease the carbon footprint of that ethanol, then the CO_2 can thereafter no longer be seen as carbon neutral.
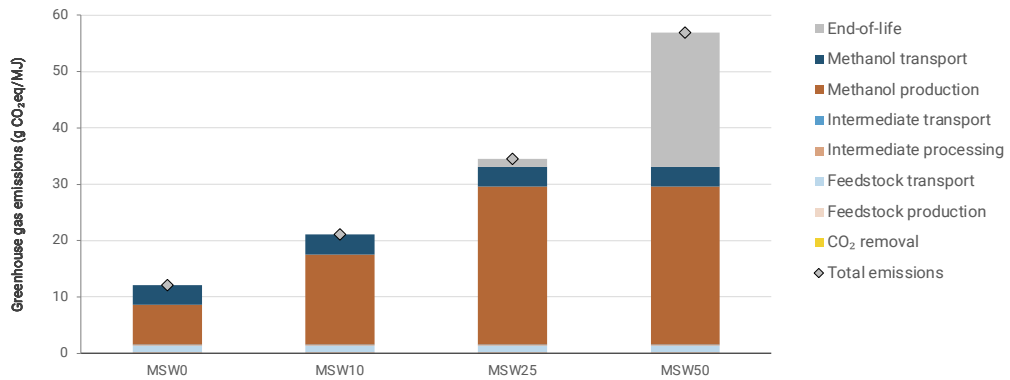
Figure 5: Carbon footprint of methanol from MSW with varying fossil contents (0% to 50%).

Savings (e_{sca}, e_{ccr}, e_{ccs})
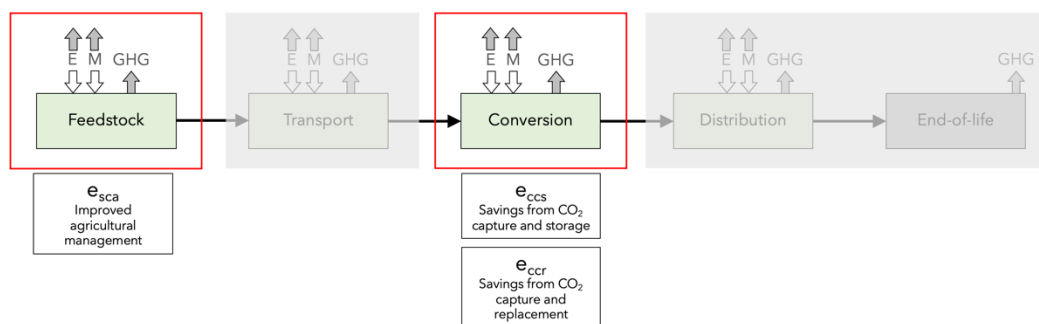
The RED II and ISCC methodology award bonusses for improved agricultural management (e_{sca}) and savings from CO_2 capture and replacement (e_{ccr}) or storage (e_{ccs}).

e_{sca} : RED II and ISCC award a bonus for emission savings from carbon accumulation in soil driven by the adoption of improved agricultural management. Improved agricultural management is e.g. shifting to reduced or zero-tillage, improved crop rotations and/or cover crops, improved fertiliser or manure management (for example the use of organic fertilisers) or the use of soil improver as compost.

e_{sca} can be calculated the same way as parameter e_l, thus calculating the change in carbon stock by subtracting the actual land use from the carbon stock of the reference land use (prior to the land-use change). The carbon stocks of the actual and reference land, annualised over 20 years, depend on the soil organic carbon and the carbon of the vegetation. The result is divided by the yield of the raw material (dry matter).

For e_{sca} a bonus of 45 g CO_2eq/MJ manure shall be attributed for improved agricultural and manure management in the case animal manure is used as a substrate to produce biogas and biomethane (see parameter e_{ec} – Biomethane from anaerobic digestion).

e_{ccr}: The emission savings from carbon capture and replacement shall be limited to emissions avoided through the capture of CO_2 of which the carbon originates from biomass. Moreover, it needs to be proven that the CO_2 replaces fossil derived CO_2.

For the calculation of e_{ccr} one must take the emissions into account resulting from the energy consumed and inputs used for capturing and processing of the CO_2 (by applying the appropriate emission factors), divided by the total energy content (LHV) of the methanol.

e_{ccs}: The emission savings from carbon capture and geological storage can only be considered if the emissions have not already been accounted for in parameter e_p. Secondly, the emissions shall be limited to emissions voided through capture and storage of emitted CO_2 directly related to the extraction, transport, processing, and distribution of the biofuel. If the CO_2 is directly stored it should be verified whether the storage is in good condition, that there are no leakages, and that the existing storage guarantees that the leakage does not exceed the current state of technology.

The calculation of e_{ccs} is the same as the calculation for e_{ccr}, thus one must take the emissions into account resulting from the energy consumed and inputs used for capturing and storing of the CO_2 (by applying the appropriate emission factors), divided by the total energy content (LHV) of the methanol.

Allocation of carbon footprints to end-product(s)

During the production lifecycle, sometimes useful co-products are produced, such as for example steam or DME. Co-products carry part of the environmental burden, because they are partly responsible for the activities up to the point they are produced (responsibility point of view) or because they avoid alternative production of the same materials via other processes (causality point of view). Lifecycle assessment methodologies include different options to deal with by products.

In the RED II / ISCC approach, so-called energy allocation is applied, which implies that the carbon impact up to the point the co-product is produced, is distributed over the products at that point, on an energy basis. Effectively, this means that each product gets the same impact per energy unit, i.e. per MJ (on a Lower Heating Value basis). Thus, at a point where multiple products are being produced, the total of emissions up to that point are divided equally over the total energy content of all products at that point.

The Lower Heating Value of methanol, and common co-products, are given in Appendix A.6.

Note that no impact is allocated to residues and wastes that are produced alongside the main product, so that all impact remains allocated to the main product. Vice-versa, if methanol is produced from a residue or waste, any emissions up to the point it came to exist are not considered.

Table 3. Example calculation of allocation for methanol from natural gas with multiple end-products. A conversion facility produces methanol and a small amount of dimethyl-ether. The resulting allocation factor of 97% implies that 97% of the emissions upstream and including the conversion process are allocated to methanol.

	Output (ktonne)	Lower Heating Value (MJ/kg)	Energy content (PJ/year)	Allocation
Methanol	971	20	19	97%
DME	20	29	0.6	3%

2.3 Relative savings and thresholds

RED II and ISCC evaluate the greenhouse gas performance of biofuels against a fossil comparator (of 94.0 g CO_2eq/MJ), to calculate relative savings (Equation 1). Also, the RED II includes threshold values that should be achieved by renewable fuels, of e.g. 60% or 70% depending on several considerations. For methanol applied as a material, or input to other processes, this may not make sense. Relative savings and thresholds are not considered in the Tool

Equation 1: Calculation of greenhouse gas saving (%) achieved by a product.

$$GHG\ savings\ (\%) = \frac{GHG\ emission\ of\ fossil\ comparator - GHG\ emission\ of\ product}{GHG\ emission\ of\ fossil\ comparator} \times 100\%$$

3 Guidance for using the methanol footprint tool

The "Carbon footprint assessment tool for methanol production pathways Version 1.0 – May 2022" (hereafter: Tool) calculates the greenhouse gas performance (carbon footprint) of methanol produced via a given pathway. It follows the ISCC methodology as explained in Chapter 2, which is in turn fully aligned to the methodology of the European Renewable Energy Directive (Directive EU 2018/2001, also known as RED II). Users can input data on their methanol production pathway, such as facility inputs and outputs, and evaluate the resulting carbon impact. Please note that studio Gear Up cannot guarantee the correctness of the results from this Tool, as they depend on non-verified, user-specified inputs.

Start, save and resume pathways

In the Pathway Management, the user can resume and delete existing pathways, or start the analysis of new pathways. This part of the Tool gives an overview of pathways that have already been calculated by the user. When resuming a pathway on a later moment, the user is directed to the last position before saving. User can start analysis of a new pathway with a unique name. The choice of feedstock is rather important as this choice influences the general layout of the pathway that is subsequently modelled. The Tool will suggest default data for the pathway, fully in line with the description of default pathways in Appendix A.1.

Data input

The user can add, or change, data in the green fields of the Tool. Green marked fields mainly relate to the input data which is required to be filled in by the user, as for example the transport kilometres of the feedstock or the product or occurring co-products. Furthermore, emissions factors can be changed by the user, for instance to represent the electricity mix of a country. Default emissions factors from ISCC EU are used in the Tool, see Appendix A.4.

Results

The Tool gives the resulting carbon footprint. The results are given in total and disaggregated values, in gCO_2eq/MJ and gCO_2eq/kg, and including or excluding end-of-life emissions.

Report

A detailed list of the results can be printed and submitted to an official auditor for review. A report is auto generated, which includes the total and disaggregated carbon footprint, including details of the emissions in the factors e_{sca}, e_{ccr}, e_{ccs}, e_{ec}, e_l, e_p, e_{td}, e_u.

4 Carbon footprint certification

Certification of biomethanol for use as a renewable fuel in the EU is possible with several schemes approved by the European Commission. Certification of any methanol for both fuel and material use is not yet a standard, but may be made possible by ISCC certification. In this section, the ISCC certification scheme is explained which can potentially be used for methanol certification.

Note that (currently) ISCC does not facilitate the certification of non-renewable fuels or materials, and for renewable fuels it does not facilitate the certification of carbon footprints only, i.e. without broader sustainability aspects.

4.1 ISCC certification principles

Every element of a supply chain for methanol needs to have an individual certification. It is necessary that it is ensured that all information of the methanol, and related (sustainability) properties, during the supply chain are preserved. The connection between the steps in the supply chain and information about the ownership, characteristics and sustainability of the materials is called the chain of custody.[27]

An adequate chain of custody requires adequate traceability, which is referred to as the ability to identify and trace the origin, distribution, location, and application of products through a supply chain. The traceability in the chain of custody ensures that all flows of materials can be traced back and forth throughout the supply chain. This furthermore guarantees the integrity of sustainability aspects.

Under ISCC, all steps of the supply chain are subject to certification (Figure 6). ISCC supplies a Proof of Sustainability (PoS) to the biofuel at the production facility on basis of a supply chain certification. Organisations along the chain are audited on a regular basis, and the chain of custody is checked on basis of contracts, bills of loading, etcetera.
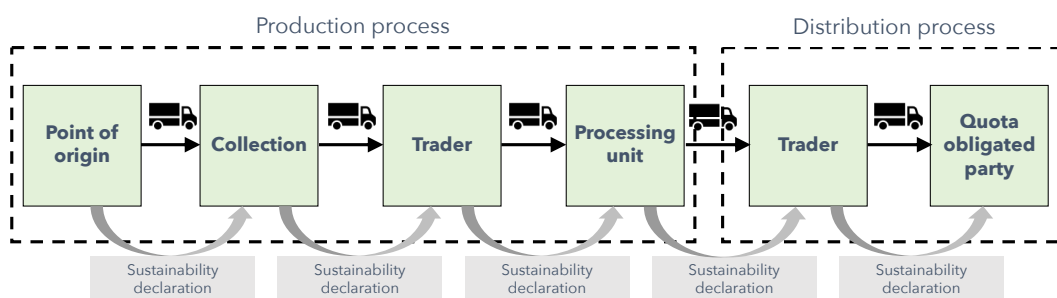
Figure 6: Step-by-Step Traceability of (Sustainability) Characteristics (through Sustainability Declarations).

The ISCC poses several requirements for audits in terms of traceability and chain of custody for declarations.

Traceability: For general audit requirements for all incoming and outgoing material, which must be met by all elements of the supply chain from Figure 6, the following information must be received by the company. This information must be up-to-date and fully accessible to the auditor in the audit process.

List with names and addresses, and contracts with relevant subcontractors/service providers, suppliers and recipients of (sustainable) methanol

Possibly: Sustainability Declarations for all incoming and outgoing sustainable material

Mass balance calculation or quantity bookkeeping in case of physical segregation (see next paragraph for more information)

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[27] ISCC Document 203 – Traceability and chain of custody.

In the case of individual greenhouse gas calculations: The calculation itself as well as the input data used for the calculation.

Within ISCC, one can apply two chain of custody methodologies, which are physical segregation and mass balance. Within ISCC, companies shall at least use a mass balance system. The first option, the physical segregation, is to keep the renewable methanol physically separated from the fossil methanol. Deliveries of physically segregated materials can be claimed to contain 100% certified sustainable material.

It is not always possible, logical or economically attractive to segregate material streams. Then a mass balance is chosen. For example, a batch of fossil and of renewable methanol necessarily travel together in a bulk tanker, see Figure 7. The different batches 1,2 and 3 are mixed to obtain batch 4. From this batch, multiple batches (5-9) are made. The mixed methanol will now consist of a fossil and a renewable part.

Depending on the amount of renewable methanol, one could still consider part of the volume to be sustainable. The sustainability properties of the material (e.g. greenhouse gas performance and other criteria) then remain assigned to the amount of the material, on a bookkeeping basis. The mass balance must contain information concerning all the characteristics and sizes of the individual parts that are mixed. The annual audits then verify that the physical input of the renewable methanol is equal, or higher, than the output.

This system is widely used and accepted in many other certification schemes to certify sustainable tea or coffee. The main benefit is that is allows for a gradual increase of renewable material depending on demand.

Input

Batch	Kind	Amount (kt)
1	Sustainable	1000
2	Sustainable	500
3	Non-sustainable	1000
Total		2500

Company process

Batch	Kind	Amount (kt)
4	Mixture	2500
Total		2500

Output

Batch	Kind	Amount (kt)
5	Sustainable	1000
6	Sustainable	250
7	Sustainable	250
8	Non-sustainable	500
9	Non-sustainable	500
Total		2500
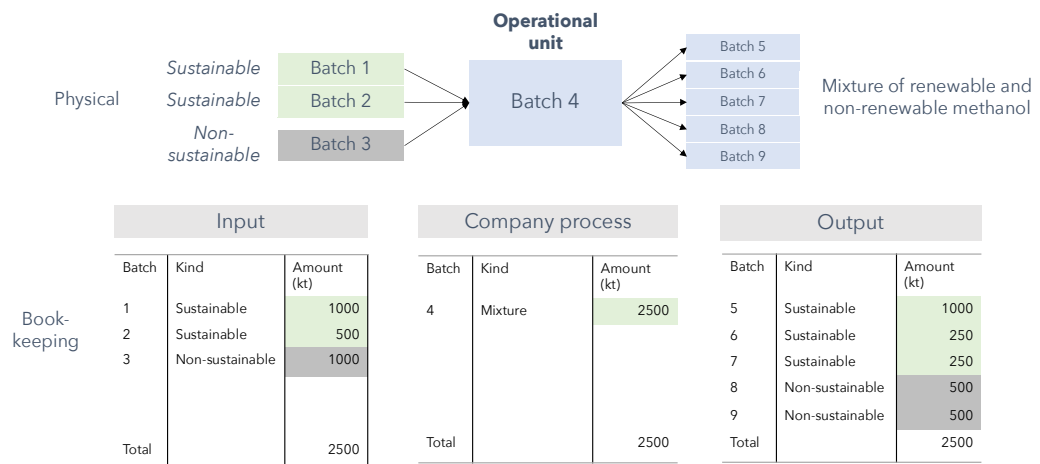
Figure 7: Example of a mixture of fossil and renewable methanol with a mass-balance system.

4.2 Guidance on how to get certified

To become certified for ISCC EU/PLUS, a company can follow the following five steps.

Step 1. Choose a certification scheme for your market

The first step is to choose a certification for your market. This means that a (basic) understanding of the ISCC certification is needed. An organisation needs to know how ISCC certification works for different commodities for different markets. The organisation needs to choose if they want to certify according to the ISCC EU or ISCC PLUS schemes, depending on the product and market (see Section 2.2.1).

However, the ISCC EU and ISCC PLUS certification schemes are largely harmonised. This means that with only one audit, multiple certificates can be issued. This nevertheless means that the organisation needs to choose one certification scheme at first.

At ISCC PLUS certification, an organisation can furthermore choose for multiple voluntary add-ons additionally to the core requirements of ISCC PLUS. These add-ons are not needed for the greenhouse gas certification described in this document. These add-ons are modules that either apply to the (agricultural) production or to the whole supply chain. Examples of these add-ons are e.g. "Non-GMO" (Add on 205-3) or "greenhouse gas emission" (Add-on 205-01).[28]

Step 2. Choose and contract a certification body

In step 2, the organisation needs to choose a certification body (often referred at as CB in ISCC-terminology). These certification bodies generally conduct audits on a global scale.

Each certification body cooperates for different certification schemes, and within different countries. This means that an organisation must carefully check which certification scheme it aims to achieve and if this certification body is cooperating in this scheme, in the respective country of the organisation. The organisation needs to sign a contract with the certification body.

An overview of recognised certification bodies can be found at ISCC website on the part of Certification Bodies.[29]

Step 3. Register at the ISCC website

After signing the contract with the certification body, the organisation needs to fill in and submit the registration form on the ISCC website. The registration must take place prior to the audit. The following information must be filled in on the registration form:

Details of the company to be registered: Name and Address details of the company to be registered.

Details of the operational unit to be certified: This address can be same as the company details. The ISCC certification is site-specific, meaning that if you want to certify multiple operational units, you need to fill in the form more than once.

Legal representative of the company

Contact person 1 (Optional: Contact person 2): This contact person is listed in the ISCC database as main contact for all issues related to ISCC updates. This person must be somebody of the company and may not be an employee of a certification body.

General information: You can choose the ISCC certification scheme which is aimed for. You can choose multiple ISCC certification schemes and, if wanted, voluntary add-ons.

Certification scope: The company must choose the applicable scopes for certification, e.g. processing unit, trader.

ISCC tariff: The company must fill in the total tons handled by the operational unit per year. This is needed for the calculation of the ISCC fees, which consists of a registration fee (one-time), a certificate fee and a quantity dependent fee.

Details about the certification body: Name and contract details (date) of the certification body.

Additional Document: The company needs to upload a copy of the company's trade register excerpt/license to operate.

Final declaration: The company needs to accept the ISCC Terms of Use.

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[28] Add-on 205-3 "Non-GMO" refers to the requirements for the certiication of crops not containing genetically modified organisms or for downstream non-GMO raw materials for the food and feed markets.

Add-on 205-1 "GHG Emission requirements" refers to the calculation methodology and verification of greenhouse gas emissions along the supply chain, including biomass production, conversions as well as transport and distribution as described in ISCC EU.

[29] See for the website: https://www.iscc-system.org/process/certification-bodies-cbs/recognized-cbs/

After positive approval by ISCC, the company receives a confirmation of the registration by e-mail from ISCC.

Step 4. Prepare for audit

The fourth step is the audit itself. After preparing the audit within the company, you can get audited by your certification body. The company must provide all necessary proofs, documents, and data. The certification body checks the audit and add, if necessary, a list with corrective measures. The company needs to implement these corrective measures.

When implemented, the certification body forwards the audit documents to the ISCC, which reviews it again. If agreed, the ISCC publishes the certificate on the ISCC website.

Step 5. Monitor and maintain

Once the (sustainability) certificate has been issued by the company's certification body, the company is allowed to purchase and sell (sustainable) material and the ISCC logo and claims can be used. There are a couple of requirements that must be complied with:

If a certificate holder buys material, it can check on the ISCC website whether the supplier is in the possession of a valid (sustainability) certificate.

ISCC System updates must be considered.

To use the ISCC logo or to claim ISCC certification, ISCC approval will be required.

Appendix A   Values for default pathways

This Appendix provides the data that is used in the default pathways included in the Tool (version 1.0 dated 1 February 2022).

For each of the feedstocks, one pathway is defined. Appendix A.1 focuses on pathway specific data, while parameters that are (in the default set-up) relevant for more pathways are reported in Appendix A.2 onwards:

Appendix A.1: Specific data for the above-listed pathways

Appendix A.2: Greenhouse gas emissions from generic transport means,

Appendix A.3: Emission factors for electricity

Appendix A.4: Emission factors for other energy and material use

Appendix A.5: Lower heating values for products and co-products

The following pathways are included in the Tool (version 1.0 dated May 2022):

Production of methanol from **natural gas** via a generic reforming process (Appendix A.1.1)

Production of methanol from **coal** via gasification and a generic reforming process (A.1.2)

Production of methanol from **biomethane** from anaerobic digestion, followed by a generic reforming process (A.1.3)

Production of methanol from **biomass** via gasification and a generic reforming process (A.1.4)

Production of methanol from **municipal solid waste** via gasification and a generic reforming process (A.1.5)

Production of methanol from **captured CO$_2$ and hydrogen** from electricity via hydrolysis and catalysis (A.1.6)

A.1 Pathway specific data

A.1.1 Natural gas

The default pathway of methanol produced from natural gas assumes:

Natural gas sourced in North America. This has a consequence for the natural gas composition, which impacts the conversion efficiency later. It also has consequences for material losses and greenhouse gas emissions during extraction, upgrading and transport.

A generic reforming of methane is assumed to produce methanol.

The data is based largely on previous work by studio Gear Up for Methanol Institute [studio Gear Up 2022, Carbon footprint of methanol].

Natural gas production, upgrading and transport

Natural gas is extracted from wells, upgraded, and transported via the gas grid. This natural gas production and transportation leads to carbon dioxide emissions related to the energy needed, and methane emissions from leakages. Methane is lost when natural gas is flared (becomes CO_2) or vented (as CH_4), and methane is also released in small leaks, called fugitive emissions, from valves and other equipment used in drilling, processing and forwarding. For the main distinctive steps, the emissions, and gas loss is given in Table A.1.

We assume that the natural gas is transported over 50 km from the wellhead to an intermediate processing point, and another 50 km to the methanol production facility.

Table A.1. Typical emissions and material losses during the extraction, intermediate processing, and transport of natural gas, in a US setting.

	CH_4 leakage and venting	CH_4 flaring	CO_2 venting	Total emissions	Total gas loss
Natural gas extraction and methane emissions at source [1]				442 gCO_2eq /kg natural gas	9.8%
Transmission [2]	46.9 gCO_2eq /tonne.km			46.9 gCO_2eq /tonne.km	0.0001675% /km
Intermediate processing [3]	6.9 gCO_2eq /kg natural gas	9.2 gCO_2eq /kg natural gas	23.5 gCO_2eq /kg natural gas	39.6 gCO_2eq /kg natural gas	2.7%

[1] IEA provides an overview of emissions from natural gas production and supply worldwide [IEA 2018, Spectrum of the well-to-tank emissions intensity of global gas production]. On average, this leads to about 5 g CO_2eq/MJ natural gas emissions related to energy for extraction (which thus originates from combusting 1.82 g CH_4/MJ natural gas) and 5 g CO_2eq/MJ natural gas from methane emissions at source (which implies this was about 0.18 g CH_4 emissions at a Global Warming Potential GWP of 28 [see Appendix A.4]). Together this equals about 490 g CO_2eq emissions per kg natural gas available after extraction (after losses). The total gas loss is about 2.0 g CH_4/MJ natural gas or 98 g CH_4 per kg or 9.8 mass %. The emission in the table (and in the Tool) are formulated on basis of material that enters a supply chain step (such as extraction). Therefore, the emissions become 490 * (100% - 9.8%) = 442 g CO_2eq per kg natural gas extracted (before losses).

[2] Emissions for natural gas transmission and intermediate processing are taken from the GREET model [GREET 2020, GREET 1 Series (Fuel-Cycle Model) Rev1]. For transmission, the CH_4 "leakage and venting" with an impact of 46.9 g CO_2eq/tonne.km (tonne of natural gas transported over one km) is assumed to concern 1.675 g CH_4/tonne.km (46.9 divided by the GWP of 28), representing a gas loss of 0.0001675%.

[3] For intermediate processing, the 6.9 gCO_2eq/kg natural gas leakage is assumed to represent 0.246 gCH_4/kg; the 9.2 gCO_2eq due to flaring per kg natural gas is assumed from 3.345 gCH_4/kg; and the 23.5 gCO_2eq/natural gas due to CO_2 venting represents just 23.5 g material/kg natural gas (no additional GWP or conversion factor needs to be applied). The total material loss is therefore 0.246 gCH_4 + 3.345 gCH_4 + 23.5 gCO_2 = 27.1 g material/kg natural gas, or 2.7%.

Natural gas composition

We have assumed a North American natural gas composition [Enbridge 2021, Chemical composition of natural gas (from supply basins in western Canada, the United States and Ontario producers)] with a density of 0.71 kg/Nm^3, a Lower Heating Value of 49 MJ/kg (both

calculated), a carbon content of 0.744 g/g, and (consequently) end-of-life emissions of 2.73 kg CO_2/kg natural gas. Sourcing gas from a different region, would have consequences for the heating value and carbon content, which would impact the methanol yield and the carbon balance of the conversion facility, see below.

Conversion of natural gas to methanol

Several process technologies exist to convert natural gas to methanol. The default pathway in the current version of the Tool applies a generic reforming process, a hybrid between steam methane reforming and autothermal reforming, based on insights from the industry. Table A.2 below presents the material and energy balance of the facility. The CO_2 emission is calculated on basis of the amount of carbon inputs and outputs. When the user changes inputs or outputs, the CO_2 emission will be recalculated.

Note that the carbon efficiency of the process, i.e. the amount of carbon in the methanol compared to carbon in the natural gas in this case is 78.0%, which is deemed to be representative for the industry.

When the composition of natural gas changes, for instance when considering a different region, the carbon content of that natural gas changes. This would impact the methanol yield (and other process parameters), as the carbon efficiency would remain roughly the same, and it would change the carbon balance.

Table A.2. Typical energy and material balance for a generic methanol production facility on basis of natural gas (average of steam reforming and autothermal reforming).[1]

	Unit	Input	Output
Natural gas	tonne/year	646,143	
Water	tonne/year	918,812	
Oxygen (as air)	tonne/year	194,867	
Electricity	GWh/year	42	
Methanol	tonne/year		1,000,000
Wastewater	tonne/year		12,808
Carbon in natural gas [2]	tonne C/year	480,730	
Carbon in methanol	tonne C/year		375,000
Total carbon	tonne C/year	480,730	375,000
Carbon efficiency to methanol	tonne C in natural gas /tonne C in methanol		78%
Balance of carbon	tonne C/year		105,730
Process CO_2 emissions	tonne /year		387,678

1) Data in the top part of the table is based on industry insights [studio Gear Up 2022, Carbon footprint of methanol]. The carbon balance is calculated by comparing the mass of carbon in inputs and outputs.

2) In this case, it is assumed that the natural gas has a carbon content of 0.744 gC/g (see above). At a lower carbon content, the yield of methanol would also decrease. Carbon content of methanol is 12/32 gC/g.

A.1.2 Coal

The default pathway of methanol produced from coal assumes:

Coal is sourced in China. This has a consequence for the coal composition, which impacts the conversion efficiency later. It also has consequences for material losses and greenhouse gas emissions during extraction, upgrading and transport.

A generic gasification of coal is assumed to produce methanol.

The data is based largely on previous work by studio Gear Up for Methanol Institute [studio Gear Up 2022, Carbon footprint of methanol].

Coal production, selection and washing

Only in China, methanol is produced from coal. Therefore, all parameters and resulting emissions for coal mining, selection and washing, and transport of coal explained below are taken from a practical example in China. The total greenhouse gas emissions from all items in the table is 594 gCO_2eq/kg coal, and mainly caused by coalbed carbon leakage.

Table A.3. Typical emissions and material losses during the mining, selection and washing, and transport of coal.[1)]

	CH$_4$ leakage	CO$_2$ leakage/ emission	Total coal loss
Coalbed carbon leak [2)]	469 g CO$_2$eq/kg coal	20 g CO$_2$eq/kg coal	
Coal consumption in heating boilers [3)]		53.8 g CO$_2$eq/kg coal	2.72% of raw coal
Electricity consumption by mining equipment [4)]		33.7 kWh/tonne coal (leads to 28.8 g CO$_2$eq/kg coal)	
Spontaneous coal combustion [5)]		19.8 g CO$_2$eq/kg coal	1% of raw coal
Electricity consumption in selection/washing [6)]		3 kWh/tonne coal (leads to 2.6 g CO$_2$eq/kg coal)	

[1)]   All data based on [Luo et al 2017, Coal Supply Chains: A whole-process-based measurement of carbon emissions in a mining city of china, MDPI Energies 10, 1855]. The coal (in the cited study) presumably concerns bituminous or sub-bituminous coal. Processed coal has Lower Heating Value of 26.3 MJ/kg, a carbon content of 0.69 kg/kg (washed) coal and end-of-life emission of 2.53 kg CO$_2$/kg coal. Emissions from coal combustion in the table are based on raw coal (0.54 kg C/kg coal), with an end-of-life emission of 1.98 kg CO$_2$/kg coal.

[2)]   Carbon emissions from mining (400 m depth) concern coalbed carbon leaks and emissions from energy use.

[3)]   About 2.72% of the raw coal is consumed in heating boilers. The raw coal has a carbon content of 54%, and an end-of life emission of 1.98 g CO$_2$eq/g coal.

[4)]   Mining equipment consumes about 33.7 kWh electricity per tonne, with a carbon intensity of 855 g CO$_2$eq/kWh, thus leads to an emission of 28.8 g CO$_2$eq/kg coal.

[5)]   Spontaneous combustion occurs (1%).

[6)]   Coal selection and washing consumes a small amount of electricity (3 kWh/tonne), again with a carbon intensity of 855 gCO$_2$/kWh.

Coal transport

On average, 75% of the coal is transported by truck over 387 km, while 25% is transported by diesel locomotive over 165 km [Luo et al 2017]. Therefore, the following parameters are used in the default pathway in the Tool:

75% x 387 km = 290 km by truck

25% x 165 km = 41 km by train

Fuel consumption and related emissions can be found in Appendix A.2.

About 1% of coal is lost during transport [Luo et al 2017].

Conversion of coal to methanol

Table A.4 below presents the material and energy balance for a methanol production facility on basis of bituminous coal, including gasification, water gas shift, methanol synthesis and rectification [NPCPI 2017, Status quo and coping strategies for carbon emission in nitrogen fertilizer and methanol industries]. The inputs and outputs are specified per year, based on an output of 600,000 tonne/year methanol and 8,000 hours/year operation time.

Table A.4. Typical energy and material balance for a generic methanol production facility on basis of bituminous coal in China.[1]

	Unit	Input	Output
Coal for product	tonne/year	1,391,305	
Coal for heat	tonne/year	288,538	
Electricity	GWh/year	733	
Methanol	tonne/year		1,000,000
Fuel gas	tonne/year		8,000
Slag	tonne/year		166,660
Carbon in coal [1]	tonne C/year	1,159,092	
Carbon in methanol	tonne C/year		375,000
Carbon in fuel gas [3]	tonne C/year		4,360
Carbon in slag [4]	tonne C/year		57,500
Total carbon	tonne C/year	1,159,092	432,860
Carbon efficiency to methanol	tonne C in natural gas /tonne C in methanol		32%
Balance of carbon	tonne C/year		726,232
Process CO_2 emissions	tonne /year		2,662,851

[1]   Data in the top part of the table is based on a case study by NPCPI [NPCPI 2017, Status quo and coping strategies for carbon emission in nitrogen fertilizer and methanol industries]. Data is comparable to what was previously presented by studio Gear Up [studio Gear Up 2022, Carbon footprint of methanol], converted from an annual production capacity of 600,000 tonne to 1 million tonne methanol (all values have been multiplied by 1.67). The carbon balance is calculated by comparing the mass of carbon in inputs and outputs.

[2]   Clean bituminous coal (following the processes described above and in Table A.3) has a carbon content of 0.69 g C/g coal. The total amount of coal used in the facility of 1391,305 + 288,538 = 1,679,843 tonne/year therefore delivers 1,159,092 tonne C/year.

[3]   Fuel gas is assumed to contain 0.545 g C/g fuel gas.

[4]   While the total amount of slag is not given by NPCPI, they state that the amount of carbon in slag is 34,500 tonne C on basis of the 600,000 tonne methanol output, or 57,500 tonne C in a 1,000,000 tonne methanol set-up. We have arbitrarily assumed a carbon content of 34.5% and from there (reverse calculation) estimated the amount of slag produced to be 166,660 tonne/year.

A.1.3 Biomethane

The default pathway of methanol produced from biomethane assumes:

Biomethane is produced by upgrading biogas, which is in turn produced via anaerobic
digestion from a mix of 50% pig manure and 50% maize silage.

The biomethane is converted into methanol via the generic reforming process as described in
Appendix A.1.1.

The data is based largely on previous work by studio Gear Up for Methanol Institute [studio
Gear Up 2022, Carbon footprint of methanol], complemented with other literature as indicated.

Production of feedstock for anaerobic digestion

Biogas can be produced from a range of crops, residues and waste streams.

If biogas is produced from crops, the production of those crops should also be taken into
account. Greenhouse gas emissions result mainly from the use of fertiliser (both during the
production and the application of fertiliser), and from the use of energy (diesel use in the
tractor during the various crop stages). Table A.5 includes aggregate results for maize silage,
per kg of crop harvested. The Tool does not allow for specification of the upstream energy and
fertiliser use. We assume the carbon intensity at the feedstock level can be taken from other
studies, or (in the EU) be provided on basis of certification.

The default pathway in the Tool concerns a mix of 50% wet pig manure and 50% dry maize
silage (by mass). This implies the average emissions from feedstock production become (-54
+ 140) : 2 = 43 g CO_2eq/kg feedstock.

Table A.5. Typical emissions during the production of feedstocks for anaerobic digestion,
reported as the resulting carbon intensity per unit of material (based on upstream emissions),
and avoided emissions from conventional treatment.

	Unit	Feedstock carbon intensity	Avoided emissions	Total
Cow manure [1]	g CO_2eq/kg manure	0	-54	-54
Pig manure [1]	g CO_2eq/kg manure	0	-54	-54
Organic waste [2]	g CO_2eq/kg waste	0	0	0
Maize silage [3]	g CO_2eq/kg dry silage	140	0	140

[1] Cow and pig manure are waste streams and therefore have zero upstream emissions attached to it, because
emissions during the growth of the animals are allocated to the products (meat, milk). When this material is
used in anaerobic digesters to produce biogas, this avoids conventional treatment (such as direct use of the
untreated manure on land), which would have caused significant greenhouse gas emissions, mainly in the
form of methane, which has a strong global warming potential. The "bonus" for avoided emissions is a
generic credit as suggested by the EU Renewable Energy Directive.

[2] Other organic waste (or residues) can be considered to have zero upstream emissions. Conventional
treatment is assumed not to cause emissions, and no bonus is applied.

[3] Strong differences in the carbon footprint of maize exist between literature sources, ranging from below 40 g
CO_2eq/kg silage up to 290 g CO_2eq/kg silage, with a mean value of about 140 g CO_2eq/kg silage. Performance
will differ per plot and depends mainly on the fertiliser input and the crop output. Note that both maize
grains and maize silage can be used in anaerobic digesters. Furthermore, ensure that moisture content of
crops harvested is equal to the moisture content assumed for the same feedstock entering the digester.
Silage typically has a much lower carbon intensity than grains, due to the much higher yield per hectare. For
a more extensive overview see our study for MI.

Transport of feedstock materials

For the default pathways in the Tool, we have assumed that the collection of feedstock takes
place in the region of the anaerobic digester, with an average distance of 50 km by truck. Note
that in reality, some digesters collect (part of) their feedstock from several hundreds of km
away. Energy consumption and resulting emission factors for transport are given in
Appendix A.2.

Conversion of feedstock to biogas and biomethane in an anaerobic digestor

At the digestion facility biogas and some digestate is produced. The biogas is then upgraded
to biomethane. During this upgrading, the biogas is cleaned, and the methane is separated

from the carbon dioxide and other gasses and components. The net yield of methane is reported in Table A.6.

The default pathway in the Tool concerns a mix of 50% wet pig manure and 50% dry maize silage (by mass). This implies that the average methane yield is (9.6 + 202) : 2 = 106 kg methane/tonne fresh feedstock.

Table A.6. Typical net yield of biogas and biomethane (after internal energy consumption) by anaerobic digestion of various feedstocks.[1] Data from the last column is used to specify the conversion yield in the Tool.

	TS (%) [2]	VS/TS (%) [3]	Methane yield		
			(Nm³/tonne VS) [4]	(Nm³/tonne fresh feedstock) [5]	(kg/tonne fresh feedstock) [6]
Manure [7]					
Dairy cows	8.5%	80%	230	15.6	10.4
Pigs	6.0%	80%	300	14.4	9.6
Sheep/goats	30.0%	80%	200	48.0	32.1
Poultry	20.0%	80%	320	51.2	34.2
Other materials					
Maize silage, dry basis [8]	100%	95.8%	316	303	202
Domestic food waste [9]	21.9%	91%	419	83.5	55.8
Wastewater sludge [9]	8.6%	77%	247	16.4	10.9

[1] Yield of biogas in most literature sources is reported in terms of Nm³/tonne feedstock. The "biomethane" after upgrading contains 100% methane, has a density of 0.668 kg/Nm³, a Lower Heating Value of 49.9 MJ/kg, and a carbon content of 0.75 g C/g biomethane (exact stoichiometric ratio of methane).

[2] TS is the total solids content: the fraction of dry material in the manure (larger part is water). TS = 100% − moisture content. One should ensure that the feedstock moisture content on basis of which the methane yield is calculated or measured, is equal to the moisture content in the feedstock production stage.

[3] VS/TS = Fraction of volatile solids in the total solids. Volatile Solids are organic solids, which transform into methane during digested, contrary to the inorganic solids which are inert in the reaction.

[4] Methane yield from volatile solids depends on the type of organic molecules prevalent per type of manure, and therefore differs per animal species.

[5] For manure derived methane, the methane yield can be calculated by multiply the previous factors: TS × VS × Yield per tonne VS.

[6] Since the Tool, in the later methanol production step calculates with a conversion efficiency on mass basis, we translate the yield into kg methane/kg fresh feedstock, applying the 0.668 kg/Nm³ mentioned in Footnote 1.

[7] All data on methane from manure digestion from [Scarlat et al 2018, A spatial analysis of biogas potential from manure in Europe, Renewable and Sustainable Energy Reviews 94:915-930].

[8] Biomethane yield from maize silage is often reported per tonne dry silage. At harvest, maize silage typically has a moisture content of 65% (typical at harvest) or a TS of 35% [Hutňan 2009, Biogas production from maize grains and maize silage]. The gas yield in the table represents DRY silage, to align with the feedstock greenhouse gas emissions of Table A.5. Note, that the biomethane yield from maize silage (302 Nm³/tonne dry silage) is only half of the yield from maize grains (605 Nm³/tonne dry grains) and these should not be confused. Maize grains are seldomly used for digestion, and their yield per hectare in the feedstock production is only 1/3 of that of maize silage (both on dry basis).

[9] There are many types of organic waste, with a wide variety of possible yields, depending on moisture content and type of material. Data on a range of household and commercial food waste, food industry waste and other organic waste streams are reported by [Browne 2013, Biomethane production from food waste and organic residues, PhD thesis, University College Cork, Ireland]. The cited numbers are only meant as an indication, and especially insights in the moisture content (TS = 100% − moisture content) should be considered to arrive at a better understanding of the methane yield from specific streams. Commercial biogas and biomethane installations may have site specific information.

Transport of biomethane

We assume the biomethane is transported over 50 km to the methanol production facility. Gas loss is as described in the natural gas pathway (Table A.1), thus 50 km * 0.0001675%/km = 0.008375%.

Conversion of biomethane to biomethanol

The conversion of biomethane to biomethanol is assumed to take place by the generic reforming process described in Appendix A.1.1. Note, however, that the inputs and carbon balance will change:

Inputs of water, oxygen and electricity are assumed to relate mainly to the methanol output, hence the values are the same as in Table A.2 for production from natural gas.

The carbon efficiency is assumed to be the same 78%. Note that, in reality, the methanol yield depends on both the carbon content of the feedstock and its heating value. The carbon efficiency may therefore be somewhat different.

With the same carbon efficiency of 78%, and same 1,000,000 tonne methanol output, the carbon input must be the same 480,730 tonne C/year. But with a carbon content of 0.75 g C/g biomethane (see footnote under Table A.5), the biomethane input is slightly lower than the natural gas input in Table A.2.

The balance of carbon, and the process CO2 emissions per tonne of methanol are the same as in Table A.2.

Table A.7. Typical energy and material balance for a generic methanol production facility on basis of biomethane (average of steam reforming and autothermal reforming).[1]

	Unit	Input	Output
Biomethane	tonne/year	640,973	
Water	tonne/year	918,812	
Oxygen (as air)	tonne/year	194,867	
Electricity	GWh/year	42	
Methanol	tonne/year		1,000,000
Wastewater	tonne/year		12,808
Carbon in biomethane	tonne C/year	480,730	
Carbon in methanol	tonne C/year		375,000
Total carbon	tonne C/year	480,730	375,000
Carbon efficiency to methanol	tonne C in natural gas /tonne C in methanol		78%
Balance of carbon	tonne C/year		105,730
Process CO$_2$ emissions	tonne /year		387,676

[1] Principles behind all values are explained in the text above the table.

A.1.4 Biomass

The default pathway of methanol produced from biomass assumes:

Forest residues are collected, transported and gasified to produce synthesis gas.

The synthesis gas is converted into methanol via the generic reforming process as described in Appendix A.1.1.

The data is based largely on previous work by studio Gear Up for Methanol Institute [studio Gear Up 2022, Carbon footprint of methanol].

Production of solid biomass feedstock

Methanol from solid biomass can be made from wood and forestry residues, short rotation coppice or other types of biomass. Table A.8 below includes some default values for typical types of biomass in generic situations.

If the biomass is cultivated mainly or only for the bioenergy application (energy is the main product), such as is likely the case with short rotation coppice, then the greenhouse gas emissions resulting from the cultivation process should be considered. This includes emissions from diesel use for farm operations as well as emissions from fertiliser use and emissions related to the production of that fertiliser. As any biomass production system is different, it is advised to calculate the specific carbon intensity of the biomass if that is possible.

If the methanol is produced from residues, the emissions during feedstock production are not accounted for (they are accounted to the main product, e.g. timber), and feedstock emissions are considered to be zero.

Table A.8. Typical emissions during the production of feedstocks for anaerobic digestion, reported as the resulting carbon intensity per unit of material (based on upstream emissions), and avoided emissions from conventional treatment.

	Feedstock carbon intensity	
	(g CO2eq/MJ fresh feedstock) 1)	(g CO2eq/kg fresh feedstock) 1)
Forestry residues 2)	0	0
Short rotation coppice 3)	18.6	167

1) Carbon intensities for feedstocks are sometimes reported on energy basis (per MJ or per GJ), and sometimes on mass basis. To calculate from energy to mass basis, one should multiply with the energy value (MJ/kg). Be aware that the energy value can be expressed on a wet and dry basis, and on lower or higher heating value (net or gross heating value in US literature).

2) Residues have zero upstream emissions by definition. Any emissions during the growth cycle are attributed to the main product. Unlike wet biomass streams (previous pathway), the conventional treatment of such biomass does not lead to high greenhouse gas emissions and therefore no bonus applies when this biomass is utilised for methanol production.

3) Emissions result from farm operation (field preparation, planting, management, fertilisation and harvesting) and can differ from field to field. CREA reports an average carbon intensity of 18.6 gCO_2eq/MJ [CREA 2020, Carbon footprint of thermal energy production from poplar short-rotation coppice plantations, Council for Agricultural Research and Economics, Italy]. We assume the biomass harvested has a moisture content of about 45% and (consequently) a Lower Heating Value of about 9 MJ/kg$_{wet}$ [Therasme et al 2019, Overhead protection increases fuel quality and natural drying of leaf-on woody biomass storage piles]. Note that "newly developed" plantations often lead to an increase (and in limited cases to a decrease) of carbon stock in the soil, depending on the previous use of the land, the new crop type and management methods. This is not considered in the data presented here.

Transport

During transport, handling and storage, material may be lost due to process technical inefficiencies and biological degradation, and drying.

We assume that the forest residues that (later) enter the methanol production facility have a moisture content of 30% and are further dried/pre-treated within that facility (see below). We assume the forest residues during the full transport contain the same 30% moisture. This implies that the chips, between harvest and transport dry from 45% moisture to 30%. This implies a 15% total mass loss due to losing water. At the same time, the Lower Heating Value

per kg increases (because drier material has a higher energy content) and the Lower Heating Value of the total feedstock volume improves slightly (because less energy will be wasted on heating water during combustion).

Furthermore, losses of dry matter could be up to 8% of the dry mass in the case of wood chips, but lower for stems (larger chunks) or pellets (treated).[30] The loss of dry matter obviously induces a loss of energy and should be avoided where possible. Due to the transportation distance (below) and the nature of the material, we assume that dry matter losses during transport and handling are 4%.

In summary, the default pathway assumes:

Lower Heating Value of fresh biomass : 9 MJ/kg$_{45\% \text{ wet}}$ (see footnote 3 under Table A.8).

Mass loss due to moisture loss : 15%

Solid matter loss : 4%

Total mass loss : 19%

Lower Heating Value of semi-dry (30% moisture content) biomass : 11.5 MJ/kg$_{30\% \text{ wet}}$

In the default pathway, it is assumed that the forest residues are transported over 100 km by truck on average.

Conversion: gasification and methanol production

The conversion of solid biomass to biomethanol is assumed to take place by the generic reforming process described in Appendix A.1.1. Note, however, that the inputs and carbon balance will change:

An additional amount of natural gas is assumed to be required for the conversion process. This then implies that the methanol facility has fossil carbon emissions (see footnotes below table for calculation and implications).

The syngas after gasification is rich in biogenic carbon. To avoid loss of valuable biogenic carbon, additional hydrogen is produced by an electrolyser integrated within the system boundaries (using part of the electricity). In the default pathway it is assumed this concerns renewable electricity from wind. If the electricity for the electrolyser would be taken from the grid, this would have a high impact on the result.

This production of hydrogen via an electrolyser furthermore requires an input of demineralised water.

Biomass usually contains between 45% and 50% (by mass) of carbon on a dry matter basis, we therefore take 47.5% carbon.[31]

The use of natural gas, electricity, water and demineralised water (and whatever further inputs there may be) has upstream carbon emissions. In the Tool, these are accounted for by applying carbon intensity factors.

As explained in the footnotes below the table, the current version of the Tool cannot account natural gas (if it is not the main feedstock) in the carbon balance. The process emissions from natural gas are therefore (at the moment) lumped into the upstream carbon impact factor for natural gas. The 30,000 tonne natural gas, at 49 MJ/kg equals an input of 1,470,000 GJ in the Tool.

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[30] Bioboost, 2013: Logistics processes for transport, handling, and storage of biomass residues from feedstock sources to decentral conversion plants (report D1.4).

[31] FAO, 2005: Carbon content of vegetation.

Table A.9. Typical energy and material balance for a generic methanol production facility on basis of biomass (average of steam reforming and autothermal reforming).[1]

	Unit	Input	Output
Biomass	tonne/year	2,000,000	
Natural gas [2]	tonne/year	30,000	
Oxygen (as air)	tonne/year	Unknown	
Electricity	GWh/year	7,200	
Water	tonne/year	8,500,000	
Demineralised water	tonne/year	928,540	
Methanol	tonne/year		1,000,000
Wastewater	tonne/year		unknown
Carbon in biomass [3]	tonne C/year	665,000	
Carbon in natural gas [4]	tonne C/year	22,320	
Carbon in methanol	tonne C/year		375,000
Total carbon	tonne C/year	687,320	375,000
Carbon efficiency to methanol	tonne C in natural gas /tonne C in methanol		55%
Balance of carbon	tonne C/year		312,320
Process CO_2 emissions	tonne /year		1,145,173
… of which have a climate impact [5]			81,840

[1]   All data as previously reported in our work for MI [studio Gear Up 2022, Carbon footprint of methanol]. The principles underlying the values are explained in the text above the table.

[2]   The use of natural gas leads to fossil emissions. In the Tool, these emissions are split in upstream emissions (for the exploration and delivery of natural gas) and emissions during use (stoichiometric emissions resulting from the combustion of the natural gas). The upstream emissions are accounted for via a carbon intensity factor, see Appendix A.4. The emissions during use are accounted for in the plant carbon balance, see Footnote 5 below.

[3]   Biomass contains 47.5% carbon on dry basis. The biomass contained 30% moisture content. Therefore, the 2,000,000 tonne biomass equals 1,400,000 tonne dry matter × 47.5% = 665,000 tonne carbon. The biogenic carbon is carbon neutral on a lifecycle basis (it was fixed in the plants by absorbing carbon from the atmosphere).

[4]   The natural gas is assumed to contain 0.744 g carbon / g natural gas (see Appendix A.1.1). In the current version of the Tool, natural gas is left out of the carbon balance of the facility and the process emissions from the combustion of natural gas are lumped into the upstream emissions.

[5]   The methanol is a biomethanol, and all biogenic energy and carbon is attributed to the methanol molecules. The largest part of the process emissions also results from the biogenic carbon and has no climate impact. The 22,320 tonne of fossil carbon leads to 22,320 × $^{44}/_{12}$ = 81,840 tonne CO_2 emissions (with $^{44}/_{12}$ being the ratio of CO_2 over C). As noted in footnote 4 above, the current version of the Tool cannot (yet) account for the natural gas in the carbon balance (in this specific case where natural gas is not the main feedstock).

A.1.5 Municipal solid waste

The default pathway of methanol produced from municipal solid waste assumes:

Municipal solid waste consists of a biogenic and a non-biogenic part.

Both parts are considered waste and therefore are considered to have zero upstream greenhouse gas emissions: any greenhouse gas emissions upstream were allocated to the useful product function before it became waste.

The collection of the waste is considered to be a necessary and unavoidable step and its emissions are not considered in the carbon footprint analysis.

The biogenic fraction is considered to have zero end-use emissions: CO_2 emissions that occur when the eventual methanol is combusted were absorbed from the atmosphere during plant growth (short carbon cycle).

The non-biogenic part is a fossil stream. The end-use emissions may be accounted for depending on the recyclability of the material:
In some cases, the non-biogenic waste stream is considered to be non-recyclable and if it was not converted to methanol, it would have been combusted or landfilled. In this case, the end-use CO_2 emissions would have taken place anyway. For the methanol they are therefore considered to be non-additional and count as zero.
However, if the non-biogenic waste stream was recyclable, its use for methanol production displaces another use which requires new fossil resources. This, de facto, is (almost) equal to the production of methanol from new fossil resources. Therefore, the end-use CO_2 emissions in methanol are considered to have a climate impact.

From a central gathering point, municipal solid waste is transported to a processing facility, where it is gasified to produce synthesis gas.

The synthesis gas is converted into methanol via the generic reforming process as described in Appendix A.1.1.

The data is based largely on previous work by studio Gear Up for Methanol Institute [studio Gear Up 2022, Carbon footprint of methanol].

Collection and nature of municipal solid waste

Upstream emissions, including those during the collection of waste, are not considered. Emissions only start to count from the central gathering point onwards.

The Tool allows for the specification of:

- Biogenic part (end-use emissions count as zero)
- Non-recyclable fossil part (end-use emissions count as zero)
- Recyclable fossil part (end-use emissions have climate impact)

The rationale behind this is explained in the introduction to this pathway above.

In the Tool, each of the three parts that the waste consists of (in the scope of the Tool), is further specified with moisture content and carbon content, so to ensure that the total volume of transported material and later carbon balances over the conversion facility are correct in relation to the amount of methanol produced, see Table A.10.

Table A.10. Typical composition and characteristics of municipal solid waste.[1]

	Fraction (%)	Moisture content (% of part)	Carbon content (% of dry matter)
Biogenic	50%	72%	46%
Non-recyclable fossil part	25%	10%	40%
Recyclable fossil part	25%	10%	40%
Resulting composition		41%	41.4%

[1] The overall composition of half biogenic, half non-biogenic, of which in turn half non-recyclable is an arbitrary example. The real composition will differ greatly between locations and seasons. Moisture and carbon content are based on an average of observations for the composition of municipal solid waste around the world [Paritosh 2018, Fraction of municipal solid waste: Overview of treatment methodologies to enhance anaerobic biodegradability].

Transport

In the default pathway in the Tool, the municipal solid waste is transported over 100 km. We assume a 5% loss of municipal solid waste during transport. We assume that the composition remains the same (for instance no additional loss through biogenic material decomposition).

Conversion of municipal solid waste to methanol

The conversion of municipal solid waste to biomethanol is assumed to take place by the generic reforming process described in Appendix A.1.1. An overview of typical material and carbon balance, and energy input is given in Table A.11.

Table A.11. Typical energy and material balance for a generic methanol production facility on basis of municipal solid waste (average of steam reforming and autothermal reforming).[1]

	Unit	Input	Output
Municipal solid waste	tonne/year	2,300,000	
fraction biogenic	tonne/year	1,150,000	
fraction non-recyclable fossil	tonne/year	575,000	
fraction recyclable fossil	tonne/year	575,000	
Natural gas	tonne/year	34,500	
Electricity	GWh/year	7,200	
Water	tonne/year	8,500,000	
Demineralised water	tonne/year	928,540	
Methanol	tonne/year		1,000,000
Carbon in biogenic fraction	tonne C/year	148,120	
Carbon in non-recyclable fossil fraction	tonne C/year	207,000	
Carbon in recyclable fossil fraction	tonne C/year	207,000	
Carbon in natural gas	tonne C/year	25,668	
Carbon in methanol	tonne C/year		375,000
Total carbon	tonne C/year	587,788	375,000
Carbon efficiency to methanol	tonne C in natural gas /tonne C in methanol		64%
Balance of carbon	tonne C/year		212,788
Process CO_2 emissions	**tonne /year**		780,222
… of which have a climate impact [2]			195,056

[1] All data as previously reported in our work for MI [studio Gear Up 2022, Carbon footprint of methanol]. The principles underlying the values are explained in the text above the table. The carbon in the municipal solid waste fractions depends on assumptions in Table A.10.

[2] 100% of the natural gas emissions and 25% of the methanol emissions. This implies that the methanol is 25% fossil and, accordingly, has end-use emissions.

A.1.6 e-methanol

The default pathway of methanol produced from electricity assumes:

Hydrogen (H_2) is produced from renewable electricity via electrolysis.

Carbon dioxide (CO_2) is captured from a nearby industrial installation, and the credit for capturing is not yet claimed (see discussion in the main report).

Hydrogen and carbon dioxide react to produce methanol.

The data is based largely on previous work by studio Gear Up for Methanol Institute [studio Gear Up 2022, Carbon footprint of methanol], complemented with other literature as indicated.

Feedstock CO_2

The process requires H_2 and CO_2. CO_2 can either be captured from other industrial installations, or from air. Some examples:

The CO_2 can come from a fossil source, for instance captured from ethylene oxide production installations, fertiliser producers, or gas or coal fired power stations.

The CO_2 come from a biogenic source, for instance captured from bioethanol production facilities or methane upgrading facilities.

The CO_2 can be captured from air by direct air carbon capture (DACC) technologies.

For the judgement of the carbon neutrality of the eventual methanol product, it is important to understand whether any credit has been taken for the capturing:

If the source is fossil, and if no one has yet taken credit for the capturing, then the end-use emissions of the e-methanol for the cradle-to-grave result, represent a delayed emission that would have taken place anyway. These emissions therefore count as zero. For the cradle-to-gate result, the avoidance of CO_2 emissions during the capture stage are regarded as carbon absorption and accounted as a negative emission.

If the source is fossil, and a credit for the capturing has already been taken by the source installation (for instance when producing blue hydrogen), the CO_2 starts with a "clean slate" which in this case means that at the end-of-life for the cradle-to-grave result, the CO_2 emissions are regarded as common positive fossil CO_2 emissions. For the cradle-to-gate result this implies that the carbon absorption at the source is not allocated to the methanol (but to the product of the CO_2 source installation).

If fossil CO_2 is produced on purpose to produce e-methanol, then (obviously) the emissions cannot be seen as unavoidable: there is no credit for absorption, and the end-use emissions are regarded as fossil, thus having a climate impact. Moreover, the emissions from the upstream emissions from sourcing and delivering the fossil energy must also be included in the carbon footprint calculation.

If the source is biogenic, and the credit for capturing is not yet taken, the CO_2 capturing is seen as effectively removing CO_2 from the atmosphere, and counts as a negative emission for the cradle-to-gate results. The cradle-to-grave results then regard the CO_2 emissions as being zero.

If the source is biogenic, and the credit for capturing is already taken (for instance in the production of bioethanol where the Renewable Energy Directive awards a credit for carbon capture and storage or utilisation), the carbon absorption at the source cannot be allocated to the e-methanol (thus is regarded as being zero) for the cradle-to-gate result, while for the cradle-to-grave result, the emission must be seen as a positive (additional) emission (contributing to climate change).

If CO_2 is produced on purpose from biomass, to directly feed into the e-methanol production, then (obviously) the absorption can be allocated to the e-methanol and the end-of-life emission is zero. However, note that in this case the CO2 cannot be seen as a waste stream, and emissions from the upstream production of the biomass must be included in the carbon footprint calculation.

If CO_2 is captured from atmosphere, we assume that the absorption can be allocated to the e-methanol and the end-of-life emission is zero.

The Tool implements this as follows: the user can indicate the origin of the CO_2 and whether a credit for capturing was allocated to the source installation, which then leads to impacts for the carbon balance of the e-methanol, see Table A.12. Note that the Tool cannot currently include the upstream emissions that would be associated with "on purpose" production of CO_2 from fossil or biogenic sources.

Table A.12. Accounting of emissions during sourcing of CO_2 and end-of-life depending on the origin of the CO_2 and whether a carbon avoidance credit has already been taken by the source installation. "0" means that the CO_2 has no climate impact, "-1" means that per tonne CO2 that is passing, actually 1 tonne is subtracted (it's either absorbed from atmosphere in the case of DACC or it's an avoided emission to atmosphere in some cases of capturing), "stoichiometric" implies that the end-of-life emissions from use of the methanol are $^{44}/_{32}$ tonne CO_2/tonne methanol.

Source of CO_2	Capturing allocatable to	CO_2 emission from feedstock sourcing	CO_2 emission from end-of-life
Fossil, CO_2 as residue	Source installation	0	Stoichiometric
	e-methanol	- 1 (avoided emission)	0
Fossil, on purpose CO_2 production		Includes upstream emissions	Stoichiometric
Biogenic, CO_2 as residue	Source installation	0	Stoichiometric
	e-methanol	- 1 (avoided emission)	0
Biogenic, on purpose CO_2 production		Includes upstream emissions	0
Direct air capture	e-methanol	- 1 (absorption)	0

When the capturing can be allocated to the e-methanol, the energy consumption of the capturing must be allocated to the e-methanol. When the capturing is allocated to the source installation, they will (likely) have accounted for the associated energy consumption. Typical energy consumption for carbon capturing is given in Table A.13.

Table A.13. Electricity and steam consumption for typical carbon capturing set-ups, per tonne of CO_2 captured.[1)]

CO_2 concentration	Typical situation	Electricity (kWh/tonne CO_2)	Steam (GJ/tonne CO_2)
5%		183	2.5
8-10%	From power station	167	2.5
10-18%		164	2.5
Pure	From ethanol or biomethane installation	0	0

[1)]   Based on [TNO 2020, Decarbonisation options for the Dutch refinery sector].

In the default pathway, we assume that CO_2 is captured from a biomass power station, at a concentration of 9%. The energy required (electricity and steam) are taken from the same power station; associated emissions are about 0.037 tonne CO_2eq/tonne CO_2 captured.

Transport of CO_2

The CO_2 is typically transported by a pipeline. If this concerns a short distance, the energy needs are assumed to be negligible. If the CO_2 is transported over a long distance, we assume it is compressed to about 153 bar, which consumes about 82 kWh/tonne CO_2 [IEA 2014, Pipeline infrastructure].

Conversion

At the conversion facility, hydrogen is produced from (renewable) electricity and demineralised water. The captured CO_2 and renewable electricity derived hydrogen react over a catalyst to produce biomethanol. An overview of typical material and carbon balance, and energy input is given in Table A.14. The electrolyser is already included in the balance. The Tool does not currently allow for a separate production of hydrogen elsewhere.

If the electricity comes from a renewable source and the methanol end-of-life emissions according to Table A.12 have no climate impact, then the methanol is renewable. However, if either the electricity is non-renewable, or the methanol end-of-life emissions have a climate impact, then the methanol is not renewable. The Tool does not judge whether the methanol should be regarded to be renewable or not. The carbon impact of the electricity is of course considered, as well as the end-of-life emissions.

The default scale of this pathway in the Tool is 1,000,000 tonne/year of methanol to fully align it with the other default pathways included. Today methanol production via electrolysis is in early development and the production scales remain small in the coming years.

Table A.14. Typical energy and material balance for a generic methanol production facility on basis of CO_2 and electricity, via an electrolyser that produces hydrogen.[1]

	Unit	Input	Output
Carbon dioxide	tonne/year	1,460,000	
Electricity (renewable or fossil)	GWh/year	8,200	
Demineralised water	tonne/year	2,700,000	
Methanol	tonne/year		1,000,000
Hydrogen	tonne/year		20,933
Carbon in CO_2	tonne C/year	398,182	
Carbon in methanol	tonne C/year		375,000
Total carbon	tonne C/year	398,182	375,000
Carbon efficiency to methanol	tonne C in natural gas /tonne C in methanol		94%
Balance of carbon	tonne C/year		23,182
Process CO_2 emissions	tonne /year		85,000

[1] All data as previously reported in our work for MI [studio Gear Up 2022, Carbon footprint of methanol]. The principles underlying the values are explained in the text above the table. The climate impact or neutrality of the CO_2 emissions from the process is the same as during end-of-life as the carbon is from the same source. This should be established on basis of Table A.13.

A.2 Emission factors for transport

Feedstock and intermediate products are transported, often either by pipeline (gas) or by truck or train (solids).

In the default pathways, we assume that methanol transport the methanol production facility to the end-user or market consists of first 20 km by pipeline, followed by 5000 km by ocean carrier.

Table A.15. Typical energy consumption and emission factors for transportation of materials by various modes.[1]

Item	Unit	Value	Source
Truck on diesel	gCO2eq/tonne/km	263	Biograce 4d
Train, running on diesel	gCO2eq/tonne/km	10	Biograce 4d
Pipeline transport (liquids)	gCO2eq/tonne/km	15.74	Biograce 4d
Pipeline transport (gas)	As described in Table A.1		
Ocean carrier transport on HFO	gCO2eq/tonne/km	6.0571	Ecoinvent 3.7

A.3 Emission factors for electricity

In order to use the most recent values available, we override values as used by ISCC [in their report ISCC EU 205 Greenhouse Gas Emissions v 4.0].

Table A.16. Emission factors for grid electricity in several regions and for various forms of renewable electricity.[1]

Item	Unit	Value	Source
Grid electricity in the EU	g CO_2eq/kWh	250	EEA [1]
Grid electricity in the USA	g CO_2eq/kWh	380	US EIA [2]
Grid electricity in China	g CO_2eq/kWh	854	Luo [3]
Electricity from PV	g CO_2eq/kWh	4	Nugent and Sovacool [4]
Electricity from wind	g CO_2eq/kWh	6.52	Nugent and Sovacool [4]
Electricity from hydro	g CO_2eq/kWh	19	IHA [5]

[1] 2019 data (most recent available) [EEA European Environment Agency 2021, Greenhouse gas emission intensity of electricity generation in Europe

[2] 2020 data [US EIA Energy Information Agency 2021, U.S. Energy-Related Carbon Dioxide Emissions in 2020].

[3] Electricity production in China emits 840.2 gCO_2/kWh + 0.053352 gN_2O/kWh (with a GWP of 265), or 854.3 gCO_2eq/kWh [Luo et al 2017, Coal Supply Chains: A whole-process-based measurement of carbon emissions in a mining city of china, MDPI Energies 10, 1855].

[4] Renewable electricity, such as wind and solar PV have a very low greenhouse gas intensity [Nugent and Sovacool 2014, Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey]

[5] Reservoirs for hydropower emit greenhouse gas emissions; the extend of emissions depends on construction, flooded area and climate [IHA 2018 Hydropower status report].

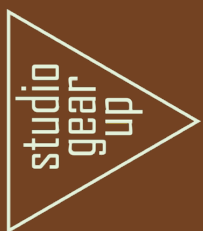## A.4 Emission factors for other energy and material use

In pathway steps throughout the calculation, materials are being used, of which the supply has a greenhouse gas impact, expressed per unit of mass or energy. We have used factors from ISCC EU 205 Greenhouse Gas Emissions v 4.0 (valid from July 2021). The factors used by ISCC stem partially from a large inventory of greenhouse gas emission factors done by the EU Joint Research Center for the purpose of calculating the carbon footprint of biofuels in the frame of the Renewable Energy Directive. Partly the factors reported by JRC stem from Ecoinvent, as indicated in the table below. Table A.17 only reports on the factors that have been used in the default pathways.

Table A.17. All the values are taken from the ISCC EU 205 Greenhouse Gas Emissions v 4.0 (valid from July 2021), except where indicated otherwise (by footnotes). Ultimate source of the parameters is indicated in the last column.

Item	Unit	Value	Source
Ammonia	[tonne CO_2eq/tonne]	2.66	EU JRC 2017 [1]
Deionised water	[tonne CO_2eq/tonne]	0.00044202	Ecoinvent v3.7
Natural gas (supply & combustion)	[tonne CO_2eq/GJ]	0.0676	EU JRC 2015 [1]
Nitrogen	[tonne CO_2eq/tonne]	0.43	EU JRC 2015 [1]
Oxygen	[tonne CO_2eq/tonne]	0.43	see footnote [2]
Process water	[tonne CO_2eq/tonne]	0.0003418	Ecoinvent v3.7
Treatment of wastewater	[tonne CO_2eq/tonne]	0.000481	Ecoinvent v3.7

[1] European Commission Joint Research Center, 2015, Definition of input data to assess GHG default emissions from biofuels in EU legislation, version 1a. Note that some data have been updated by JRC in the latest version 1d, but these newest values have not yet been adopted by ISCC.

[2] Pure oxygen is assumed to be produced together with nitrogen from air. Energy consumption and consequently the greenhouse gas emissions are distributed equally over oxygen and nitrogen by mass.