METHANOL INSTITUTE

CARBON FOOTPRINT OF METHANOL

The Methanol Institute engaged Amsterdam-based independent consultancy firm studio Gear Up to provide a Lifecycle Carbon Assessment of various methanol production feedstocks and processes based on data supplied by a dozen companies using the European Renewable Energy Directive (RED II) methodology.

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CONTENTS

KEY FINDINGS

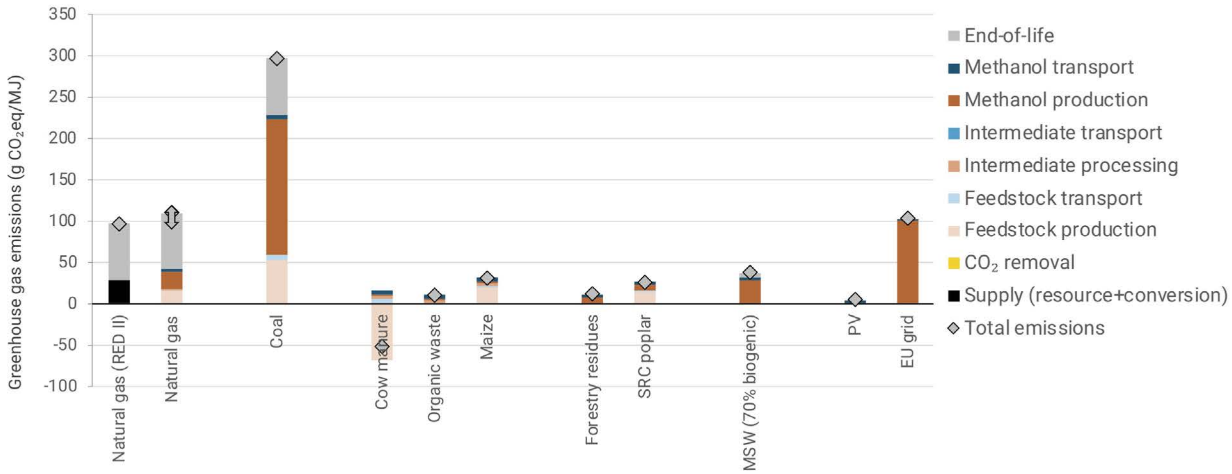

Figure 1: Carbon Footprint of Methanol Pathways

- The carbon footprint of methanol depends on the feedstock and the production pathway, taking into account all the emissions caused directly by the supply chain and by energy and materials used in the supply chain. A core element of the study is based on the carbon balance of methanol production: the calculation of how much carbon enters the facility via feedstock and fuel, and how much leaves via the products (methanol), while assuming that the difference leaves the facility principally as CO_2 .

- The majority of emissions in fossil pathways concern the stoichiometric end-of-life emissions, when using methanol as a fuel for internal combustion engines in cars, trucks, buses and ships. In pathways based on renewable feedstocks these emissions are climate neutral resulting in a significant reduction in overall climate emissions as the carbon footprint greatly improves.

- Variations within feedstock in the same category, technological differences in the installation set-up, and supply chain differences cause a significant difference in the lifecycle carbon footprint results.

- Due to the differences in outcomes one should ***not*** apply default carbon footprint factors for fossil or renewable methanol or even per feedstock category. Instead, the carbon footprint of methanol should be measured and certified to account for individual plant-specific differences – as is advised for any fuel.

- Most methanol is currently produced from natural gas, where natural gas is used both as a feedstock and as a process fuel. CO_2 emissions from the facility are accounted for by using a carbon mass balance methodology. Modern facilities today produce methanol with an estimated carbon footprint of about 110 g CO_2 eq/MJ, which is higher than what was considered state-of-the art two decades ago, of about 97 g CO_2 eq/MJ, most likely because the insight in carbon accounting has improved with data in the current study. The footprint is especially sensitive to the source of the natural gas. When sourced from the less carbon emitting sources of natural gas, the methanol supply chain emissions can decrease to about 103 g CO_2 eq/MJ. When exhaust CO_2 is recycled back to the methanol reactor, the production of methanol increases and facility emissions decrease, and as a result the lifecycle emissions per MJ of product decreases to 93-101 g CO_2 eq/MJ. These results are between 4 g CO_2 eq/MJ better and 13 CO_2 eq/MJ higher than the value used in calculations by EU Joint Research Centre JRC under RED II [EC JRC 2017a].

- Production from coal only takes place in China and has a higher carbon footprint of nearly 300 g CO_2 eq/MJ, due to large emissions associated with both the mining of coal and the methanol conversion process.

- Production from renewable sources, such as from biomethane, solid biomass, municipal solid waste (or MSW, which contains a considerable fraction of organic waste), and renewable energy, has a low carbon footprint. Most of these pathways achieve 10-40 g CO_2 eq/MJ, and some pathways even have negative emissions (-55 gCO_2 eq/MJ for methanol from biomethane from cow manure) which means effectively that CO_2 is removed from the atmosphere or that the pathway avoids emissions that would have otherwise taken place in other processes.

Background

Carbon footprint insights for methanol in the literature are scarce and often outdated. To increase our understanding of carbon footprint assessment within the industry, and at the same time obtain insights in the current status of methanol climate impacts, the Methanol Institute (MI) engaged Amsterdam-based independent consultancy firm studio Gear Up (sGU) to conduct a lifecycle carbon footprint assessment (LCA) study of multiple methanol production feedstocks and processes. In this project, sGU calculated the carbon footprint of methanol from data supplied directly by 12 companies and this white paper presents the aggregated and anonymised results.

The Methanol Institute represents methanol producers, distributors, consumers, and technology leaders across the globe. Worldwide, most methanol is currently produced from fossil energy sources, mainly from the steam reformation of natural gas. Several companies are producing methanol from renewable sources, and more companies are developing processes to produce methanol from a variety of renewable sources: bio-methanol from biomethane, biomass or municipal solid waste gasification; and e-methanol produced by combining green hydrogen from the electrolysis of water using renewable electricity and sources of carbon dioxide.

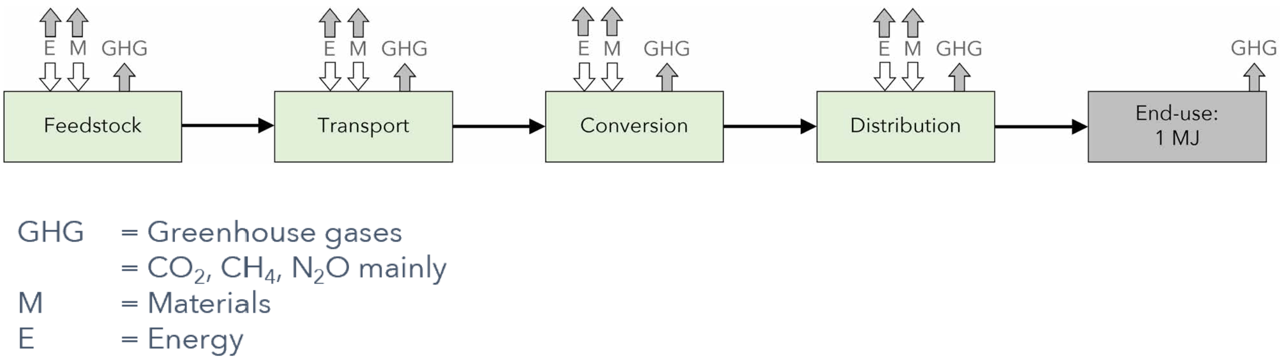

Figure 2: Methodology for Complete Lifecycle Greenhouse Gas Emissions Inventory

The study is based on a detailed insights gleaned directly from individual producers. Twelve companies participated in the project, supplying data on their process, feedstock and products, and additional energy consumption, based on existing facilities currently producing as well as production projects in active development. The carbon footprint calculations in this report constitute a lifecycle assessment, albeit only on the climate impacts. All major greenhouse gasses are taken into account (CO_2, CH_4 and N_2O mainly) and expressed in CO_2 equivalent units. More specifically, the calculations are performed in line with the European Renewable Energy Directive, known as RED II [EC 2018]. The methodology of the RED II is simple and straightforward and while it was intended for calculating the carbon footprint of biofuels, it can be extended (relatively) easily to address any type of feedstock, or combinations of multiple feedstocks. A bespoke tool was developed by sGU to apply the method of the directive.

It was considered to (also) apply the GREET model, developed by Argonne National Laboratory in the USA. This model is often used to understand the climate impact of fuels and vehicles in the American market. 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 utilizing or selling CO_2, or to combine multiple feedstocks or technology pathways in a single facility. While the GREET model was viewed as less flexible in calculating other pathways and feedstocks, several parameters have been derived from the GREET model and used in this bespoke tool.

The main difference between GREET and the RED II methodology resides in the treating of 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 (and answer different questions). GREET requires a deeper understanding of co-products which is often not available and is subject to changes over time and geographically. RED II gives consistent results and is (in this aspect) easier to apply.

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 with regard to dealing with co-product allocation. With variations on the ISO standards one could come to different outcomes for the same supply chain or conversion pathway, especially if there are important co-products. The method applied in the current study is in line with the ISO guidelines, but it is more targeted to renewable fuels. Provided that the input factors for utilized materials and external energy are the same, the expected outcomes between the different models – RED II, GREET and ISO – would not differ greatly (as methanol has few or no co-products).

Natural Gas Pathway

In general, methanol produced from natural gas has a somewhat higher or lower carbon footprint than that of fossil diesel and gasoline depending on the sourcing of the natural gas and the set-up of the facility. With state-of-the-art technologies, such as CO_2 recirculation, the carbon footprint of the facility can be improved. In cases where CO_2 is captured from the facility exhaust emissions (and used elsewhere or sequestered underground), the facility emissions can become near zero.

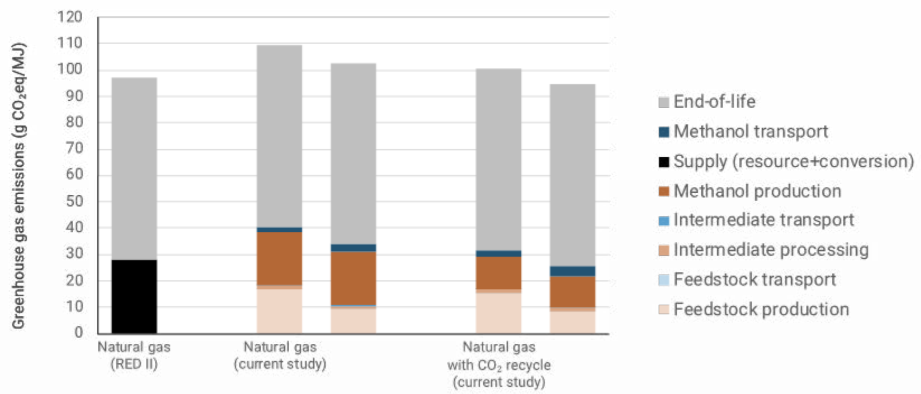

Figure 3: Emissions from the Production of Methanol from Natural Gas

However, the majority of the lifecycle emissions reside in the end-of-life stage, for instance when the methanol is combusted in a ship or other transport vehicle. These emissions are stoichiometric and cannot be avoided. They are the same for any methanol. However, if part of the feedstock carbon is supplied from a sustainable resource such as CO_2 captured from other installations, or if part of the energy is supplied from renewable electricity (via electrolysis and hydrogen), these end-of-life carbon dioxide emissions become partially net climate neutral, and the lifecycle carbon footprint of the methanol decreases.

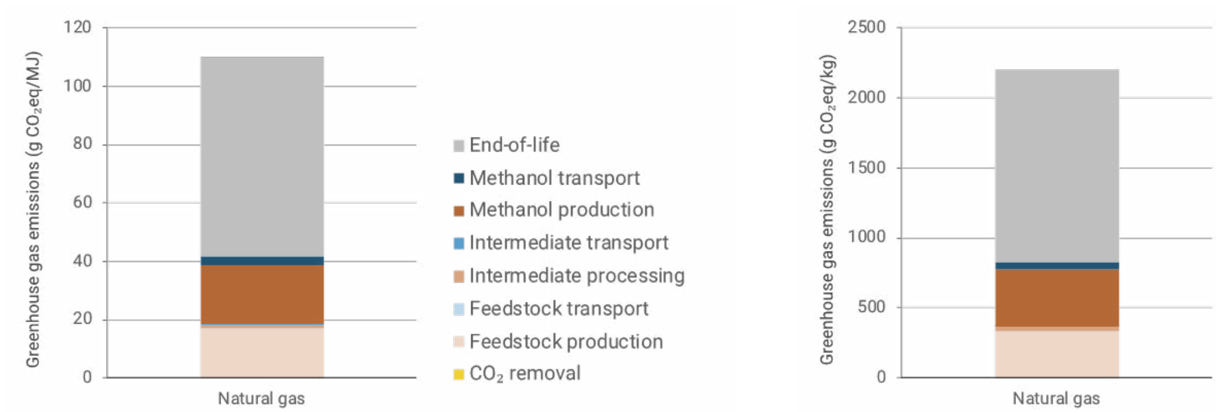

Figure 4: Methanol from Natural Gas Full Lifecycle Emissions on Energy Basis (left) and Mass Basis (Right)

In the full lifecycle emissions for the natural gas pathway, the end-of-life emissions of the methanol are included. This is relevant if methanol is used as a fuel and is therefore (eventually) combusted. This representation is also known as well-to-tank or well-to-wheel. Results are expressed per MJ LHV (left) and per kg of methanol (right). The end-of-life emissions are based on the methanol molecule: for each gram of fossil-based methanol 44 / 32 gram of CO_2 is emitted. This equals 69 g/MJ LHV . This means that the largest part of the lifecycle emission cannot be avoided when natural gas or another fossil resource is the feedstock. Full lifecycle emissions for natural gas-based methanol, via state-of-the art technology, are 103 – 110 g CO_2 /MJ LHV or 2.05 – 2.20 kg CO_2 eq/kg. The higher end of the range is shown in the graphs and represents average natural gas wells globally [IEA 2018]. The lower end is only possible if natural gas is sourced from wells with low fugitive methane emissions, flaring and energy requirements. In the shown case, the end-of-life emissions represent 62% of the total lifecycle emissions.

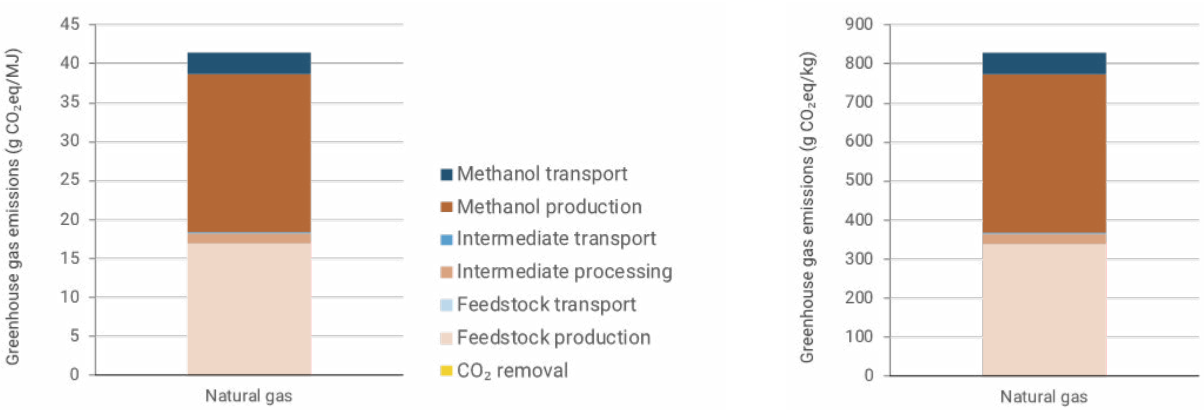

Figure 5: Methanol from Natural Gas Supply Chain Emissions (ie. Well-to-Tank)

Because the end-of-life emissions of fossil-based methanol are fixed, it is useful to have a detailed look at the supply chain emissions, excluding the methanol end-of-life emissions. The analysis here is based on data from four facilities which display a variety of technologies, applying steam methane reforming (SMR), autothermal reforming (ATR) and hybrid set ups. The installations are relatively new (all from within the last decade), so will ***not*** be reflective of the industry average across the entire fleet of natural gas-based methanol plant currently operating around the world.

If the methanol is to be used as a fuel, the upstream emissions are usually called well-to-tank. Supply chain emissions result from the production of the natural gas (fugitive, flaring and venting), transport of the natural gas (energy consumption and spills), the methanol production itself (energy consumption and stack emissions), and methanol transport to final customer. Upstream emissions from natural gas sourcing on average are about 11.4 g CO_2 eq/MJ natural gas, or 568 g/kg natural gas, mainly depending on the fugitive methane emissions, flaring and energy consumption involved in the production of natural gas, with smaller impacts from natural gas downstream processing and transport. This contributes about 17 g CO_2 eq/MJ or 367 g CO_2 eq/kg methanol to the total methanol supply chain emissions.

These emissions could be halved in the best cases (10% lower bound of emissions from natural gas observed globally, but it could also double in the worst case (10% upper bound). IEA identified the opportunity to reduce the average natural gas supply related emissions globally with about 50% [IEA 2019]. This would reduce the supply chain (and total lifecycle) emissions by some 9 g CO_2 eq/MJ methanol. For a modern natural gas to methanol process, the emissions from the production process are typically about 20 g CO_2 eq/MJ or 400 g CO_2 eq/kg methanol. The exact carbon balance over the installation depends on the carbon content of the natural gas feedstock. For instance, Northwest European gas has a carbon content of 63%, whereas Canadian gas has a carbon content of about 70%. A higher carbon content may increase the carbon emissions from the installation, or if the technology can make optimal use of it, it may increase the product yield. The emissions from methanol transport (5000 km by bulk tanker ship assumed) are relatively small in comparison to natural gas sourcing and conversion.

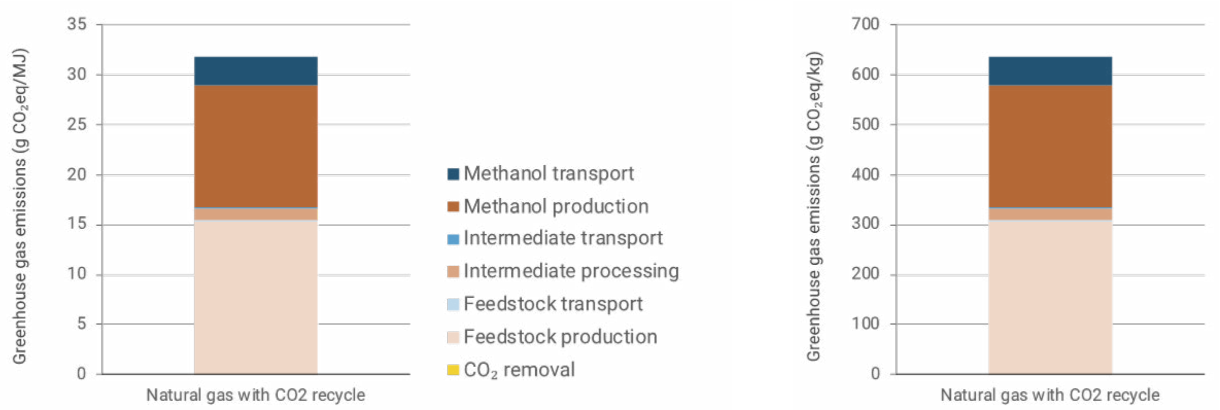

Figure 6: Methanol from Natural Gas with CO_2 Recirculation Supply Chain Emissions (ie. Well-to-Tank)

Several methanol production facilities apply CO_2 recirculation to further increase methanol production and reduce their overall carbon footprint. At the same time this consumes CO_2 that would otherwise be vented. The combined effect (less emissions from the facility, divided over more product) of a 10% increase in methanol production (as observed in one installation) can therefore reduce the lifecycle carbon footprint by about 10 g/MJ. If both the upstream emissions from natural gas supply are reduced and CO_2 recirculation is applied, methanol could have a carbon footprint of around about 93 g CO_2 eq/MJ (25 g CO_2 eq/MJ upstream emissions + 69 g from combustion). Note that the scope for applying CO_2 recirculation within existing facilities is limited by reactor sizes and other bottlenecks throughout the entire installation.

Coal Pathway

Methanol from coal as produced in China has a very high carbon footprint. Most of the lifecycle emissions reside in the conversion process and could be avoided by a better carbon management in the installation (CO_2 recirculation, capture and sequestration). Furthermore, significant emissions take place in the mining, cleaning and transportation of the coal feedstock. Some of these emissions may be avoidable, but this was not assessed for this study. If part of the feedstock carbon or energy input would be replaced by renewable sources, the end-of-life emissions could become partially net neutral, which effectively means a reduction of the carbon footprint.

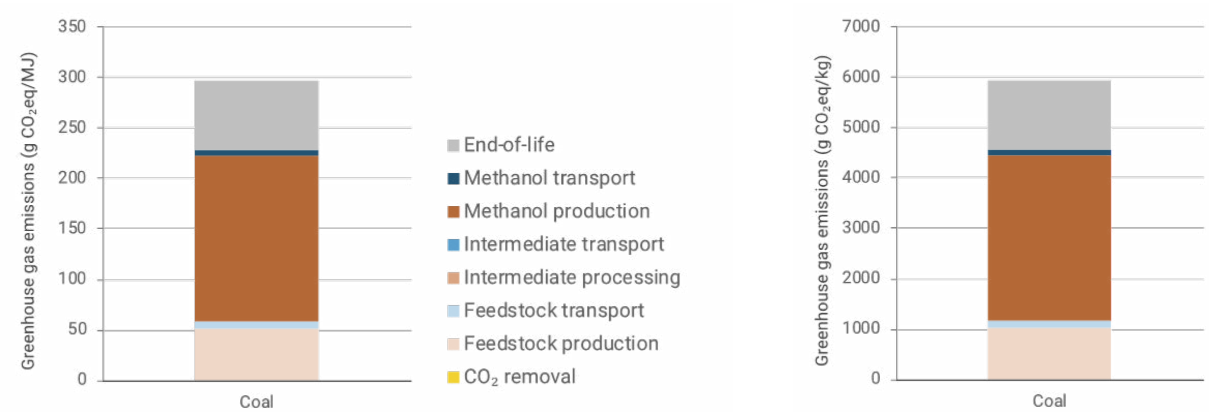

Figure 7: Methanol from Coal Full Lifecycle Emissions

The carbon footprint of methanol produced from coal is nearly 300 g CO_2 eq/MJ, which is about 3 times higher than that of natural gas-based methanol. Again, significant improvements are possible in the conversion process, via CO_2 recirculation as is observed in natural gas-based facilities, but no information about such technological improvement options for coal were readily available in the current literature. The end-of-life emissions are (stoichiometrically) the same as for all fossil-based methanol, namely 69 g CO_2 eq/MJ.

Bio-Methanol Pathways

For this study, bio-methanol pathways were defined as: biomethane-based methanol; solid biomass-based methanol; and methanol from municipal solid waste.

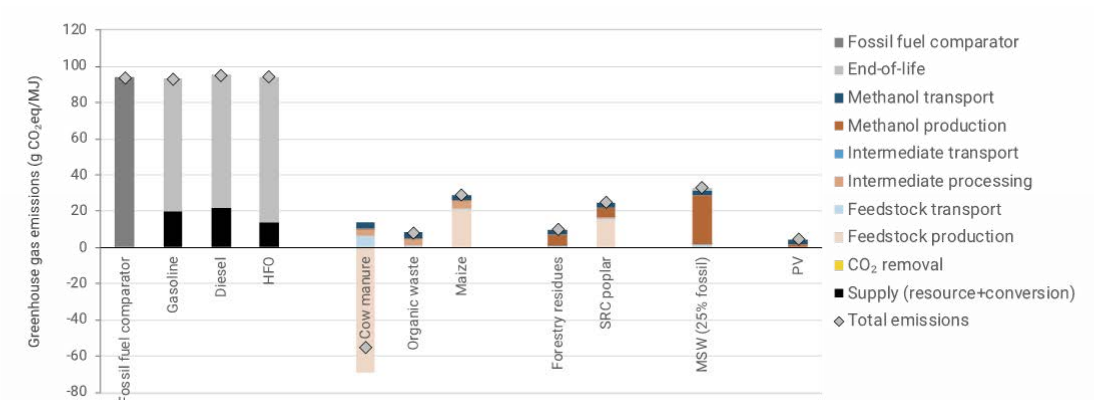

Figure 8: Carbon Footprint of Renewable Methanol and EU RED II GHG Emission Reduction Thresholds

When methanol from renewable sources is sold as renewable fuel in the EU market,[1] it has to achieve at least 50%, 60% or 65% emission reduction in comparison with the fossil fuel comparator of 94 g CO_2 eq/MJ according to RED II. The exact threshold depends on when the installation started operation, with the strictest 65% threshold for installations that started from 2021 onwards. The main advantage of bio-methanol is that the end-of-life emission count as zero, because the end-of-life emissions were previously absorbed from the atmosphere (in the case of biogenic feedstock). All renewable methanol in this overview achieves the 50% emission reduction threshold for renewable fuels produced in installations that started peration before 6 October 2016. With improvements in feedstock production (maize), or processing technology (only produce from biogenic and non-recyclable fraction in MSW), it should be possible for all renewable pathways to achieve the 65% threshold.

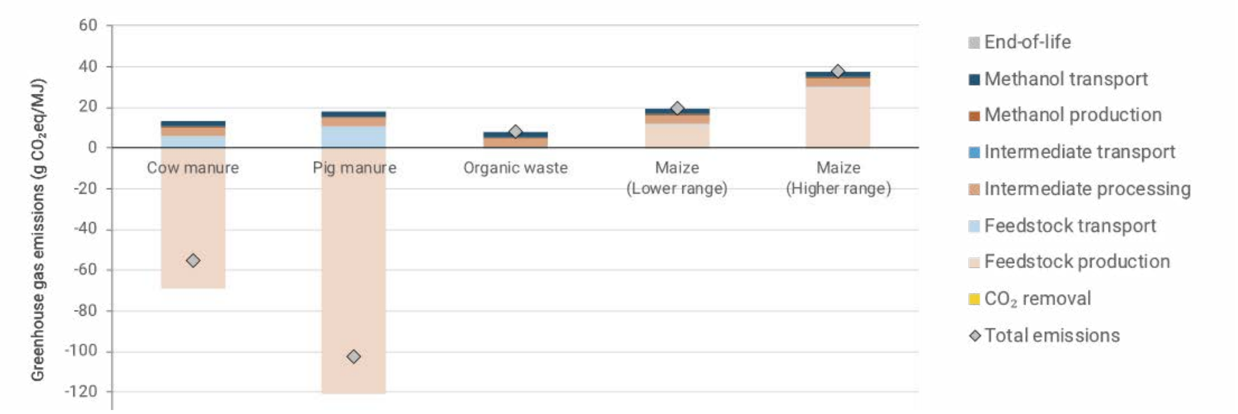

Figure 9: Methanol from Biomethane Supply Chain Emissions Depend on Feedstock

The end-of-life emissions from methanol from biomethane are climate neutral and therefore not counted. When based on manure, the production of biomethane via anaerobic digestion avoids emissions that would have taken place during alternative treatment (or no treatment) of methane. Therefore, such biomethane has a negative carbon footprint, and subsequent methanol avoids >100% emissions in comparison with fossil fuel comparators. When based on organic residues or some types of crops the carbon footprint is low and an emission reduction of >80% is achieved. On basis of other crop feedstock the emission reduction is still above 65%.

[1] Renewable fuels for transport in the EU market are stimulated by the Renewable Energy Directive and the Fuel Quality Directive. With the Fit-for-55 policy package, renewable fuels in shipping will furthermore be stimulated by the FuelEU Maritime and the inclusion of shipping in the ETS. This means that renewable fuels will obtain a market value above those of fossil fuels. Renewable methanol, either in the form of waste-based or advanced biofuel, or as e-fuel, is seen as an interesting option for the shipping sector.

Biomethane is produced in an anaerobic digestion facility and via the gas grid transported to a methanol production facility. Furthermore, the same technology, mass and energy balances are assumed as for the natural gas pathway. Methanol produced from biomethane has a carbon footprint that can vary from -103 to +38 g CO_2 eq/MJ in the pathways assessed. 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). Note that it is not economically attractive to use only manure or waste streams. Digestion of cow manure avoids conventional treatment and the associated methane emissions. The Renewable Energy Directive therefore awards a bonus of 45 g CO_2 eq/MJ manure or 54 kg CO_2 eq/t fresh matter (regardless of the type). Biomethane from manure thus has a negative footprint. Due to the efficiency losses when converting biomethane into biomethanol, the negative emissions per MJ increase: Biomethanol is rewarded for being an effective manure remover per unit of product, and a lower conversion efficiency magnifies this effect. The manure feedstock component of the biomethanol is in all cases about 1.6 – 1.8 times larger than that of the biomethane intermediate product which will have a cost. For maize the bandwidth of results relates to variations in the cropping system, crop yields, and in the amount and application of fertiliser.

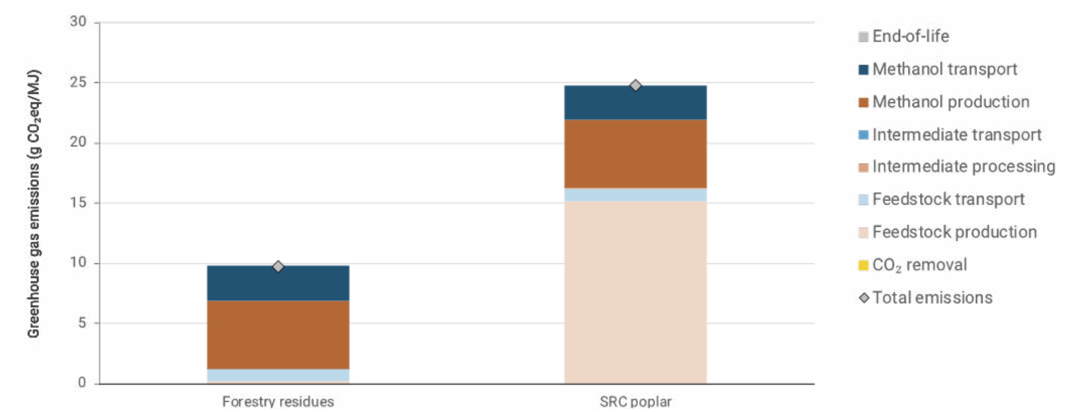

Figure 10: Methanol from Wood Supply Chain Emissions Depend on Type of Biomass

The end-of life emissions from methanol from solid biomass are climate neutral and therefore not counted. When the feedstock consists of (sustainably managed) forestry residues or short rotation energy crops, the overall carbon footprint is low and the emission reduction is above 70 - 80%. Methanol produced from wood has a carbon footprint between 10 and 20 g CO 2 eq/MJ depending on the type of wood. Forest residues have no emissions associated with the feedstock production, assuming they come available at a central point, with all previous energy use allocated to the main product, i.e. timber or pulpwood. Some types of forestry residues reqire some processing at the source location, such as bundling or chipping, which would incur feedstock production emissions. Short Rotation Coppice (SRC) poplar is an energy crop grown in a plantation setting, with limited inputs of energy and fertiliser [JRC 2017b]. Emissions of the methanol production are associated with the consumption of natural gas (as defined in the natural gas pathway) and electricity (wind power).

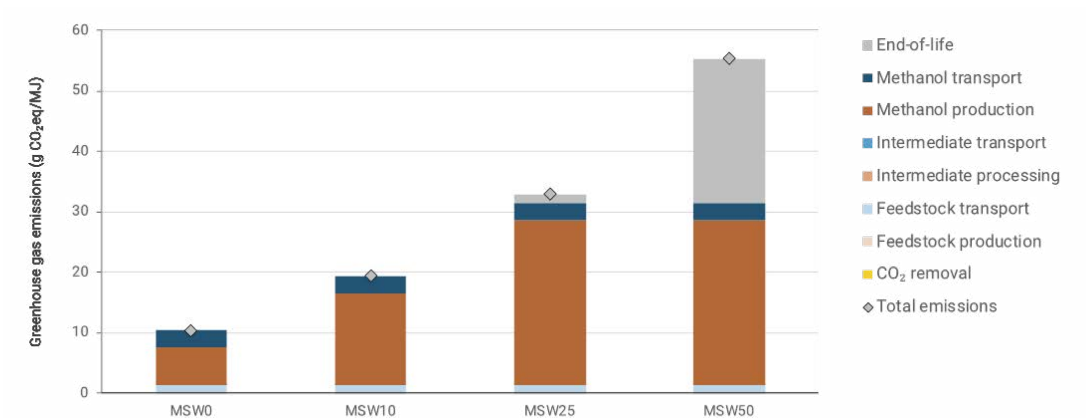

Figure 11: Methanol from Municipal Solid Waste Supply Chain Emissions Depend on Share of Recyclable

The carbon footprint of methanol from municipal solid waste (MSW) depends on the fraction of organic waste, and on the judgement of the nonorganic part of the waste. High fractions of organic waste and of (otherwise) non-recyclable material will lead to a low carbon footprint and high savings. If the non-organic fraction consists for a large part of recyclable material, then it may not be considered a waste and the carbon footprint increases.

Methanol produced from MSW has a carbon footprint of 10-55 g CO_2 eq/MJ depending on the composition of the MSW if the fossil carbon content increases from 0% to 50%. If all carbon in the MSW is of biogenic origin, or if the non-biogenic share is considered to be climate neutral, then the overall emission can be as low as 10 g CO_2 eq/MJ (MSW0 case). The limited emissions of the methanol production 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. The graph shows how first the climate emissions from the process increase, and then the emissions from end-of-life increase when moving to 10%, 25% or 50% non-climate neutral carbon in the MSW.

E-Methanol Pathway

E-methanol is produced by combining green hydrogen using renewable electricity and water electrolysis with a source of carbon dioxide. Assuming that the source carbon dioxide is renewable or originates from the captured and unavoidable emissions from another process, the end-of-life emissions have no net climate impact. The carbon footprint of methanol produced from solar PV, wind or hydropower sourced electricity is low and an emission reduction of >90% is achieved.[2] However, if electricity is sourced from the grid then the emissions associated with the feedstock production rise steeply and the lifecycle carbon footprint can even be above that of the fossil fuel reference. The main advantage of e-methanol produced from renewable electricity is that the end-of-life emission counts as zero, and as the feedstock carbon dioxide is sourced from biogenic resources, direct air capture, or emissions that were captured from industrial sources (and would have taken place anyway).

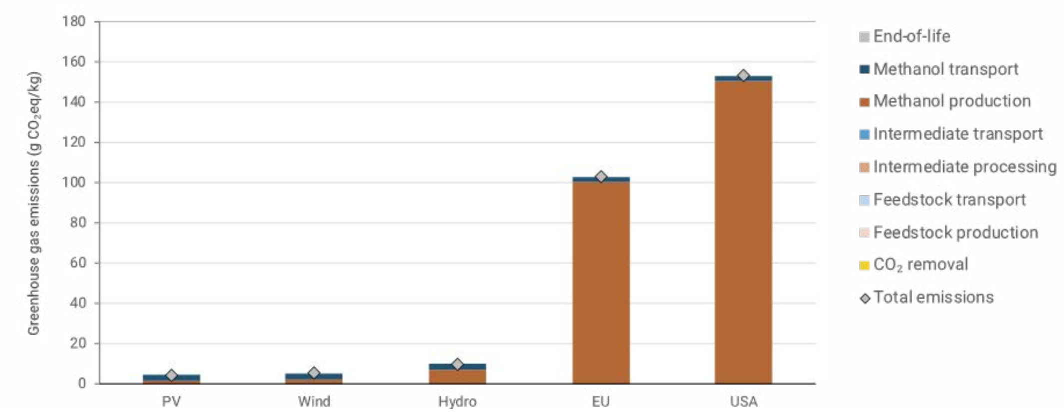

Figure 12: E-Methanol Supply Chain Emissions Depend on Source of Electricity

[2] In literature, renewable electricity is sometimes associated with a small greenhouse gas emission. Emissions related to the construction phase are ignored in the current assessment, because capital goods are excluded in the RED II carbon footprint methodology. The operational phase of renewable electricity induces some emissions: from decomposing biological material in hydropower installations, from maintenance and lubricant use in wind turbines, and from cleaning of solar PV panels. The resulting greenhouse gas emissions from renewable electricity production are near zero. Combined with some other greenhouse gas emissions along the supply chain, the lifecycle emission reduction of renewable electricity based methanol will be between 90% and 100%.

E-methanol is produced by combining hydrogen and carbon dioxide over a catalyst. It is assumed that the CO_2 is provided from an industrial source “across the fence” and does not include any feedstock transportation. If the source carbon is climate neutral, then the end-of- life emissions are set to zero. This is for instance the case when the CO_2 is generated from biomass, captured from flue gas, or captured from air. When the hydrogen is produced from solar PV electricity, the lifecycle carbon footprint of e-methanol can be small, about 4.4 g CO_2 eq/MJ, which implies an emission reduction of >90% compared to natural gas-based methanol. If instead, electricity is sourced from the grid, the associated emissions rise steeply. With an assumed EU grid performance of 275 g CO_2 eq/kWh, the lifecycle carbon footprint becomes >100 g CO_2 eq/MJ, which means that the emissions would be higher than for methanol from natural gas.

Literature

- EC JRC 2017a, Definition of input data to assess GHG default emissions from biofuels in EU legislation
- EC 2018, RED, Directive 2018/2001 on the promotion of the use of energy from renewable sources, Annex V.C
- IEA 2018, Spectrum of the well-to-tank intensity of global gas production
- IEA 2019, Methane tracker report
- EC JRC 2017b, Solid and gaseous bioenergy pathways: input values and GHG emissions

THE METHANOL INSTITUTE (MI)

FOUNDED IN 1989

Serves as the global trade association for the methanol industry representing the world's leading methanol producers, distributors and technology companies, the mission of the Methanol Institute (MI) is to serve and provide cost-effective value to its membership from our offices in Singapore, Washington, D.C., Brussels, Beijing and Delhi.

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