Carbon footprint of methanol

For: METHANOL INSTITUTE

Date: January 2022

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Colophon

Title	**Carbon footprint of methanol**
Commissioned by	Methanol Institute
Authors	Carlo Hamelinck, Mark Bunse
Background	Carbon footprint insights for methanol are scarce and often outdated. The Methanol Institute would like to increase the understanding of carbon footprint assessment within the industry, and at the same time obtain insights in the current status of methanol climate impacts. In this project, we calculated the carbon footprint of methanol for 12 companies and developed detailed individual reports (confidential). This – main - report presents the aggregated and anonymised results, a detailed description of the underlying methodology and the main findings of the project.
Disclaimer	The carbon footprint calculations have been prepared on basis of data received from the participating companies. The research was carried out between January and October 2021. studio Gear Up makes no statements about the quality of the data received.
Date	January 2022

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Introduction

Introduction

Methanol Institute

- The Methanol Institute represents methanol producers across the globe. The far majority of methanol is currently produced from fossil energy sources, mainly from 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: e-fuels from renewable electricity, biomethanol, etcetera.
- Methanol is an important base chemical and, when produced from renewable sources, methanol is amongst others interesting as a low carbon alternative fuel for shipping. The Methanol Institute requires adequate and up-to-date information on the environmental performance of methanol, as well as a comparison to the fuels it proposes to replace. Furthermore, methanol using industries increasingly ask for insight in the carbon footprint of the methanol they buy, in an endeavour to lower their own carbon footprint.
- The carbon footprint, or greenhouse gas performance of methanol can be calculated through accounting for all material and energy inputs and outputs in the production and supply chain. 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. However, the underlying data for such calculations is typically thin and sometimes up to 25 years old.
- For a fruitful conversation with methanol using industry, shipping industry and renewable energy policy makers, the Methanol Institute needs harmonized calculations based on the latest insights.

Approach and deliverables

- Therefore, this study project aims to update the carbon footprint insights, with harmonized and detailed carbon footprint calculations of major methanol production pathways from different types of fossil and renewable feedstock.
- The study is based on a detailed insights of individual producers. 12 companies participated in the project. They supplied data on their process, feedstock and products, and additional energy consumption. On basis of the information supplied, the carbon footprint was calculated for the methanol produced by these participating companies and individual reports have been developed. The individual reports are not shared with the Methanol Institute, because they contain commercially sensitive information.
- In the current report, the results from the individual calculations are summarised in an aggregated and anonymised manner. Also, this report further details the underlying methodology.

Methodological notion

Methodology of the EU Renewable Energy Directive was applied

- 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 methology of the RED II is simple and straightforward and can be extended (relatively) easily to address any type of feedstock, or combinations of multiple feedstocks. Although the methodology was developed for biofuels, it can be applied to all fuels
- A bespoke tool was developed to apply the method of the directive. The full methodology is described in the annexes.

Methodology of GREET was deemed less suitable for current calculations – but some parameters have been used

- 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 utilising or selling CO_2, or to combine multiple feedstocks or technology pathways in a single facility. The GREET model is not flexible to calculate other pathways and feedstocks.
- Several parameters have been derived from the GREET model.

Main difference

- 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. 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 more consistent results and is (in this aspect) easier to apply.

[EC 2018, Directive 2018/2001 on the promotion of the use of energy from renewable sources, Annex V.C]

Carbon footprint of methanol via different pathways

Carbon footprint of methanol
Key findings 1/2

Overarching findings

- The carbon footprint of methanol depends on the feedstock and the production pathway.
- The majority of emissions in fossil pathways resides in the stoichiometric end-of-life emissions. In pathways based on renewable feedstock these emissions are climate neutral. This causes a significant reduction in climate emission and the carbon footprint greatly improves.
- Good performing methanol from renewable sources can achieve a large emission saving in comparison with fossil reference fuels such as gasoline, diesel or current marine fuels.
- 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 (renewable) methanol should be measured and certified to account for the individual differences – as is advised for any renewable fuel.

Natural gas based methanol

- In general, methanol from natural gas or coal has a high carbon footprint, somewhat higher or lower 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. When CO_2 is captured from the facility exhaust emissions (and used elsewhere or sequestered underground), the facility emissions can become near zero.
- 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 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.

Coal based methanol

- Methanol from coal 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.
- 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.

Carbon footprint of methanol
Key findings 2/2

Biomethane based methanol

- The end-use 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%.

Solid biomass based methanol

- The end-use 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 from municipal solid waste

- The carbon footprint of methanol from municipal solid waste depends on the fraction of organic waste, and on the judgement of the non-organic part of the waste.
- High fractions of organic waste and of (otherwise) non-recyclable material 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 from renewable electricity in combination with captured carbon

- Assuming that the source carbon dioxide is renewable or concerns 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 or wind sourced electricity is low and an emission reduction of >90% is achieved.
- When using hydroelectricity, the carbon footprint increases, but still the savings compared to fossil based methanol are considerable.
- 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.

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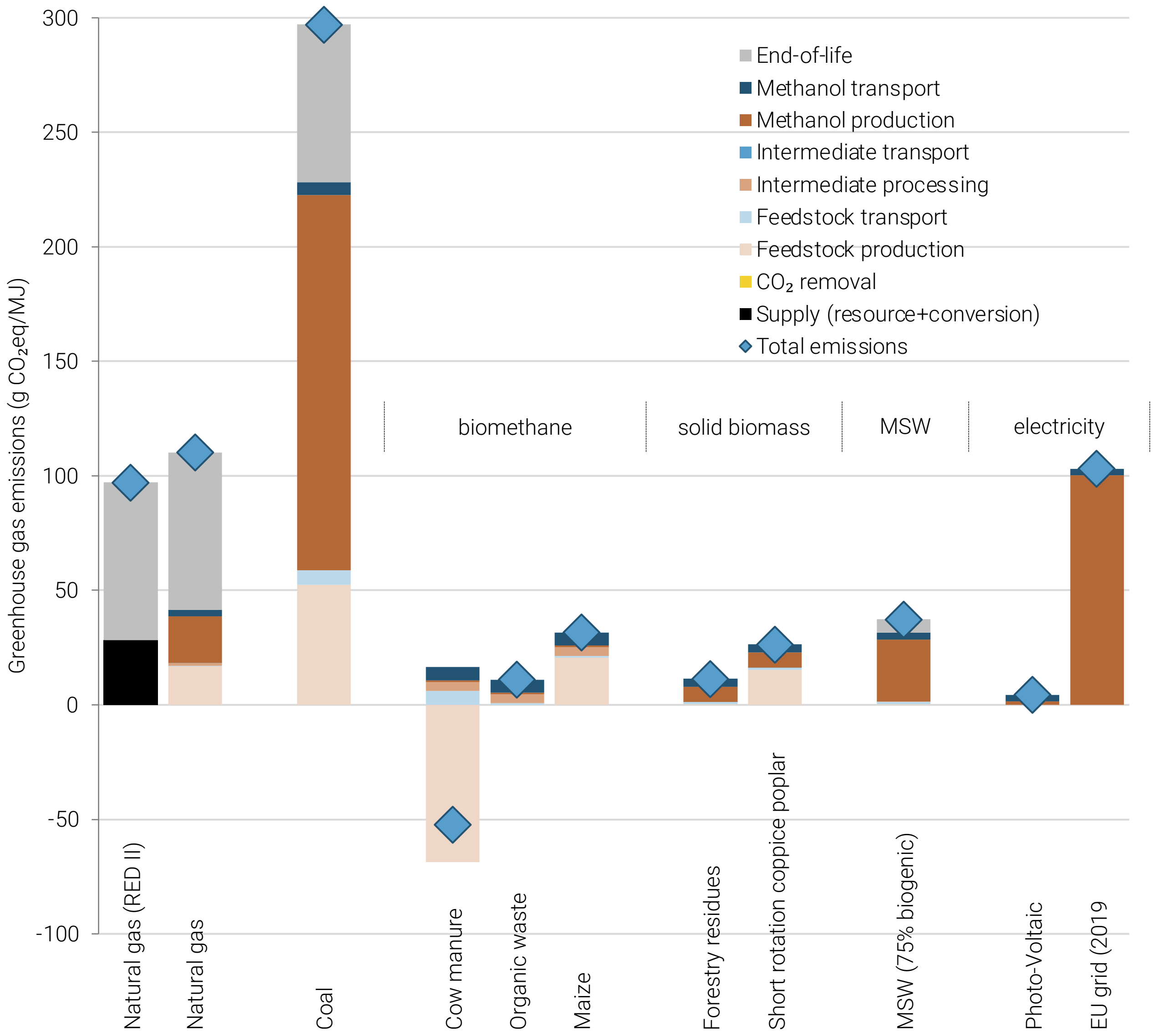
Carbon footprint of methanol
depends mainly on the feedstock

- Methanol produced from different feedstocks varies considerably in carbon footprint performance.
- Most methanol is currently produced from natural gas. Modern facilities today produce methanol with an estimated carbon footprint of about 110 g CO_2eq/MJ, which is higher than what was considered state-of-the art two decades ago, of about 97 g CO_2eq/MJ, most likely because the insight has improved with data in the current study.
- Production from coal only takes place in China and has a high carbon footprint, of nearly 300 g CO_2eq/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_2eq/MJ, and some pathways even have negative emissions (-55 gCO_2eq/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 from other processes.



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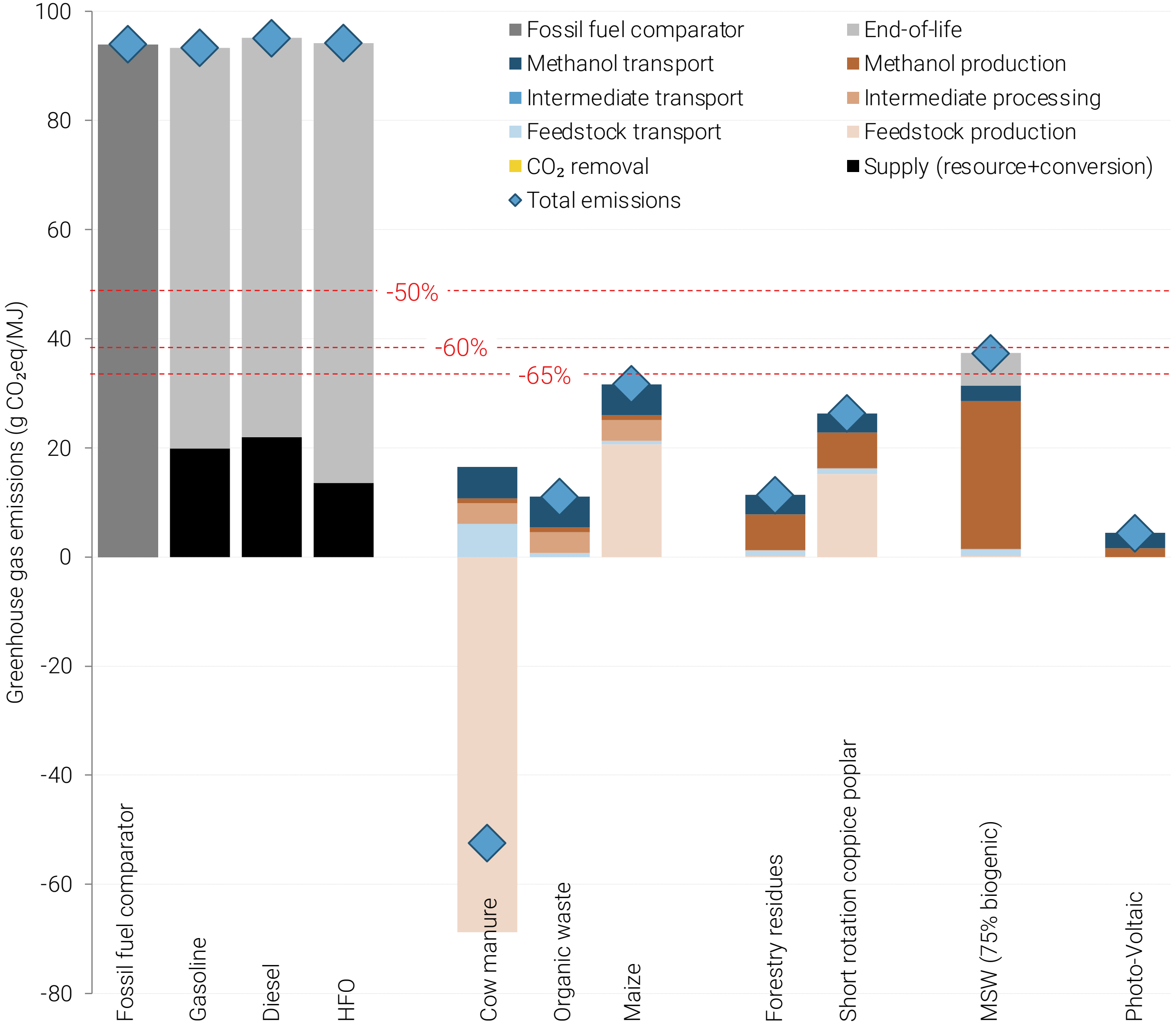
Carbon footprint of renewable methanol
can achieve the EU RED II greenhouse gas emission reduction thresholds

- When methanol from renewable sources is sold as renewable fuel in the EU market, it has to achieve at least 50%, 60% or 65% emission reduction in comparison with the fossil fuel comparator of 94 g CO_2eq/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 renewable methanol is that the end-use emission counts as zero, because the end-use emissions were either previously absorbed from the atmosphere (in the case of biogenic feedstock), or de facto delayed emissions that were captured from industrial sources (in the case of e-methanol produced from renewable electricity.
- All renewable methanol in this overview achieves the 50% emission reduction threshold for renewable fuels produced in installations that started operation before 6 October 2016. With improvements in feedstock production (maize), or processing technology (only produce form biogenic and non recyclable fraction in MSW), it should be possible for all renewable pathways to achieve the 65% threshold.



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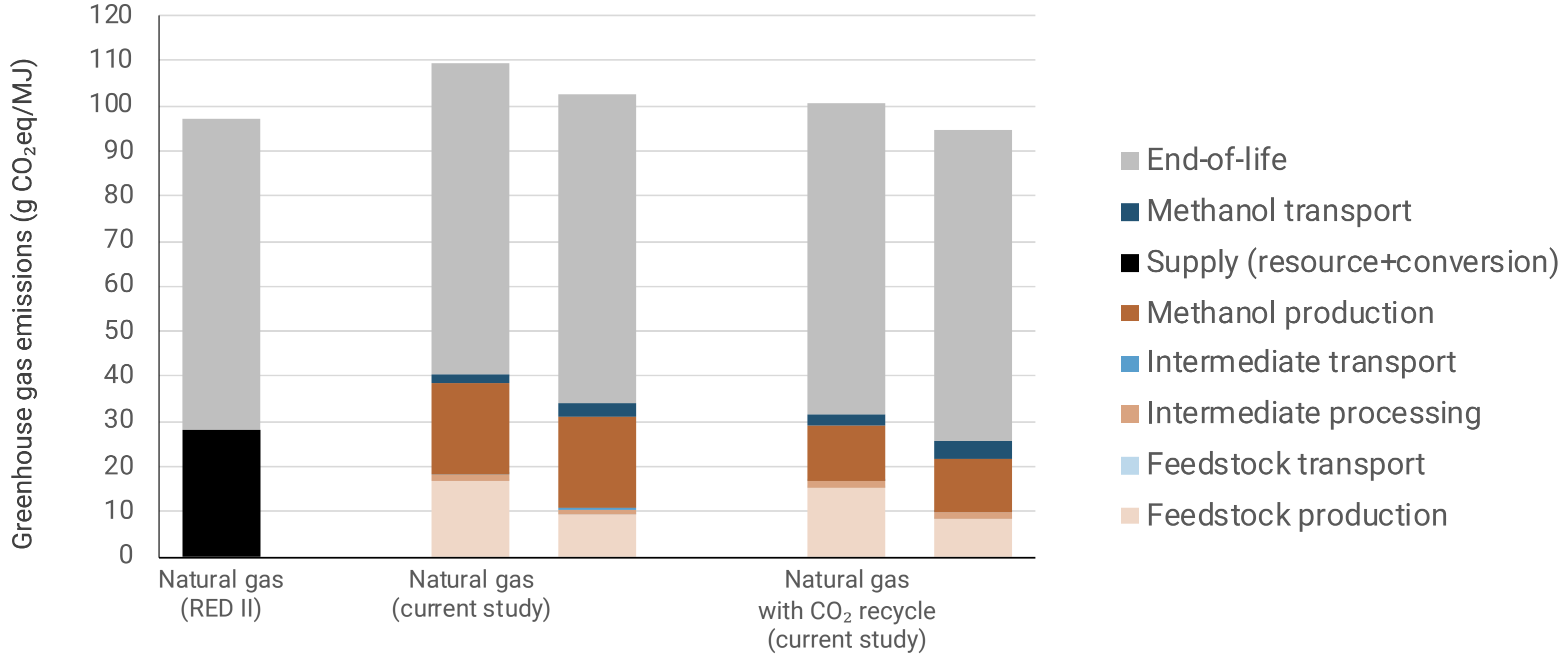
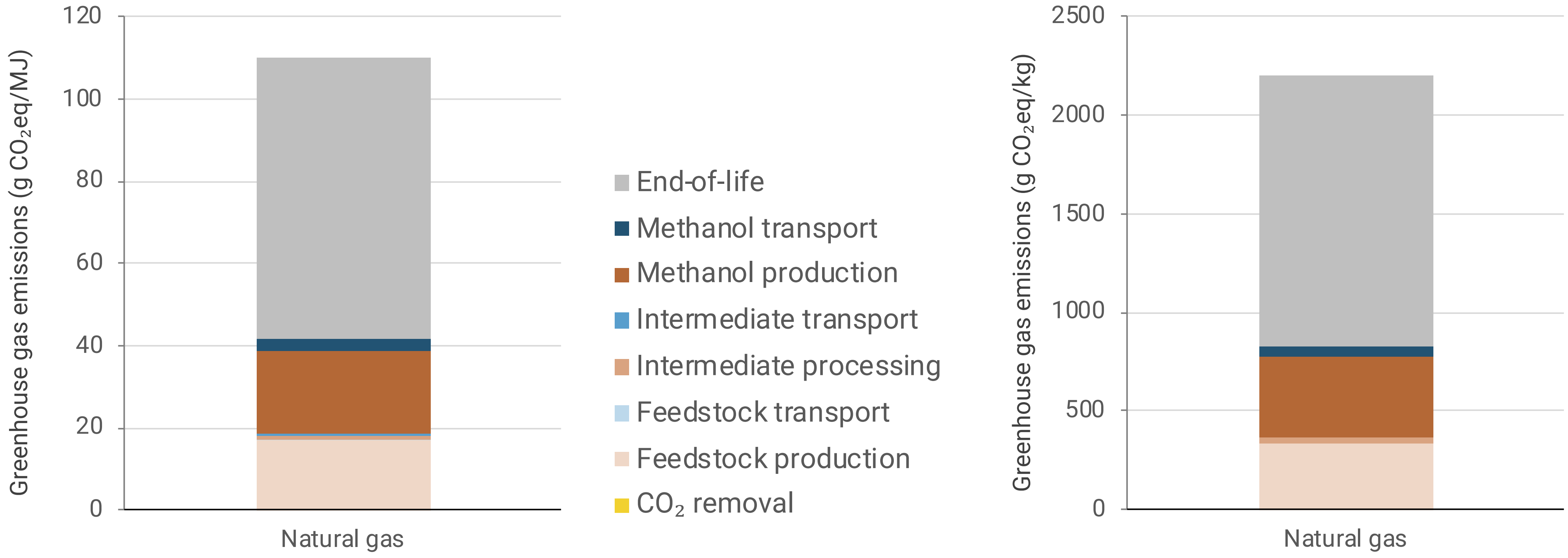
Emissions from the production of methanol from natural gas



- Methanol produced from natural gas in a state-of-the-art methanol production facility has a carbon intensity of about 110 g CO_2eq/MJ. The footprint is especially sensitive to the source of the natural gas. When sourced from the less emitting sources today, the methanol supply chain emissions can decrease to about 103 g CO_2eq/MJ. A same effect will be achieved by improvements projected by IEA towards 2030.
- 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 decrease to 93-101 g CO_2eq/MJ.
- These results are between 4 g CO_2eq/MJ better and 13 CO_2eq/MJ worse than the value used in calculations by EU Joint Research Centre JRC for the recast Renewable Energy Directive (RED II) [EC JRC 2017].
- Note that the end-of-life emissions are defined by the chemical structure of methanol and are (always) 69 g CO_2/MJ_{LHV}. The difference between the results above is therefore completely determined by the well-to-tank emissions arising mainly from natural gas production and the conversion process, and furthermore discussed on the next page.
- Furthermore, note that the JRC "resource+conversion" emissions only concern emissions from the conversion process and upstream natural gas. The current study includes high emissions from the exploration and transport of natural gas, *and* includes the transport of methanol to customer.
- The calculation of carbon intensity is in line with the greenhouse gas accounting methodology of RED II Annex V.C.
- Underlying parameters of the JRC report and current study are explained in the Annexes (Page 20 and onward).

[EC JRC 2017 Definition of input data to assess GHG default emissions from biofuels in EU legislation]

Methanol from natural gas
Full lifecycle emissions



- In the full lifecycle emissions the end-of-life emissions of the methanol are included. This representation is relevant if methanol is used as a fuel and is therefore (eventually) combusted. This representation is also known as well-to-wake 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_2eq/kg. The higher end of the range is shown in the graphs and represents average natural gas wells globally. The lower end is only possible if natural gas is sourced from wells with low fugitive methane emissions, flaring and energy requirements, as further discussed on the next page.
- In the shown case, the end-of-life emissions represent 62% of the total lifecycle emissions..

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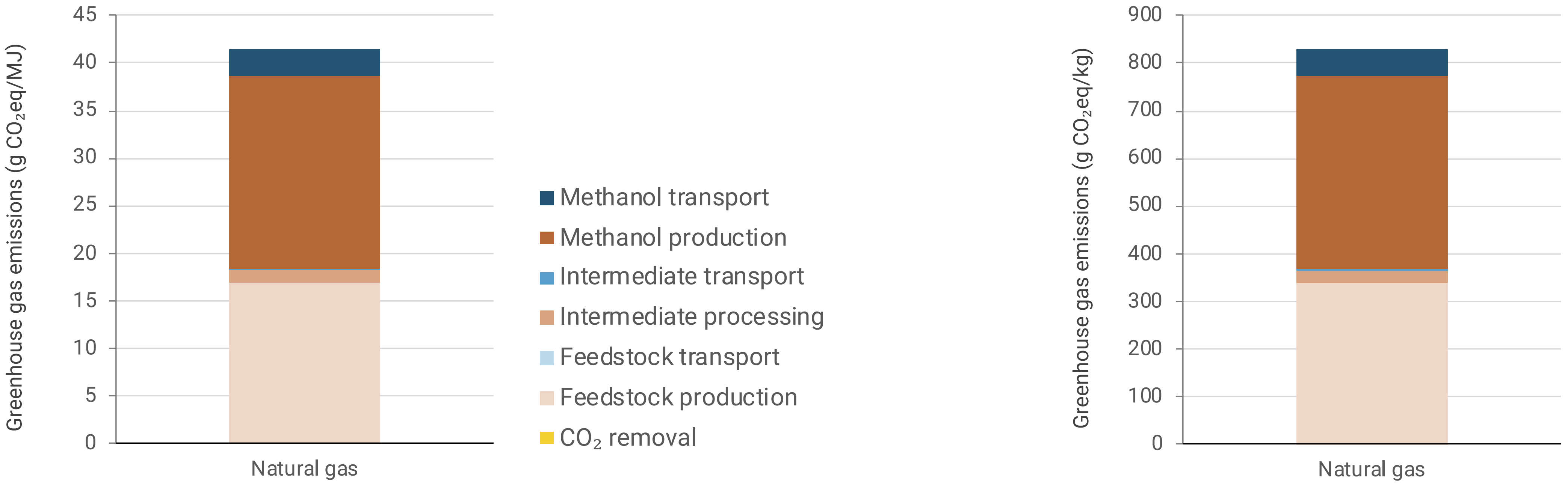
Methanol from natural gas
Supply chain emissions



- 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. If the methanol is to be used as a fuel, this scope is 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_2eq/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_2eq/MJ or 367 g CO_2eq/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, see Page 25), 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 with some 9 g CO_2eq/MJ methanol.
- For a modern natural gas to methanol process, the emissions from the production process are typically about 20 g CO_2eq/MJ or 400 g CO_2eq/kg. The exact carbon balance over the installation depends on the carbon content of the natural gas feedstock. For instance, North West 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

[IEA 2020, Spectrum of the well-to-tank emissions intensity of global gas production & Methane Tracker 2020]

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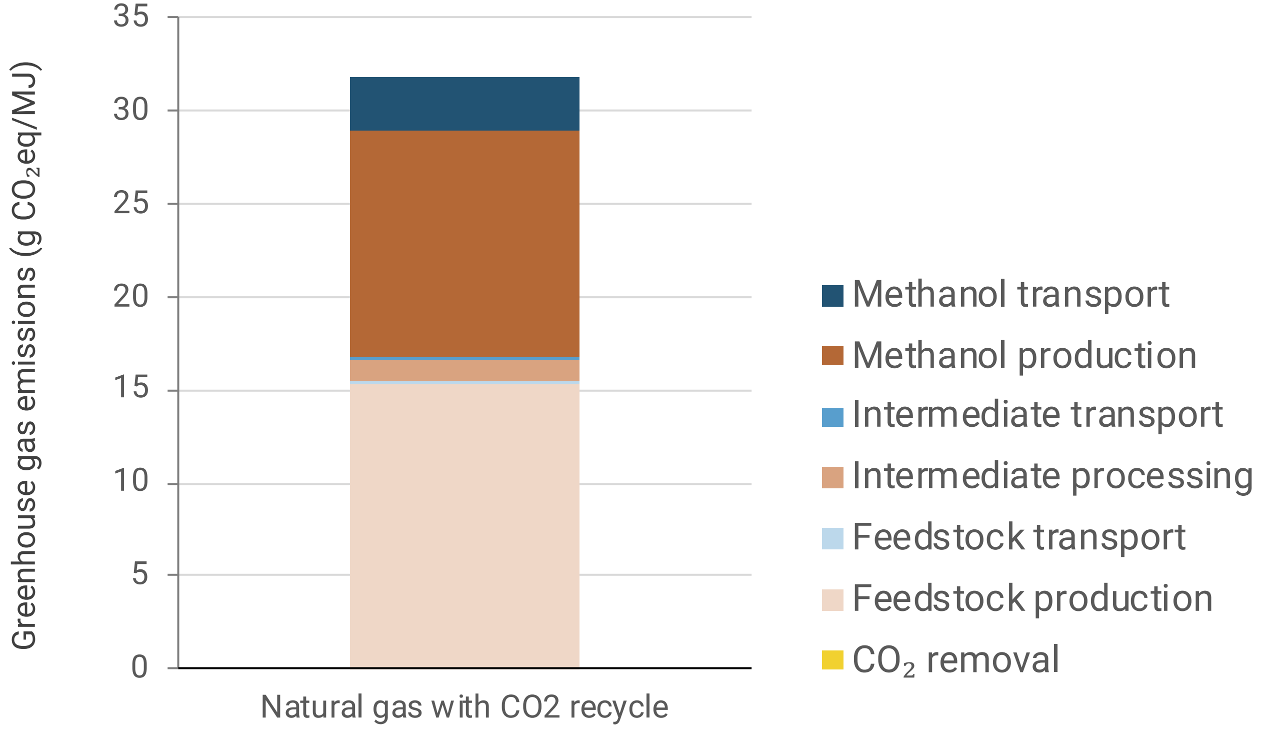
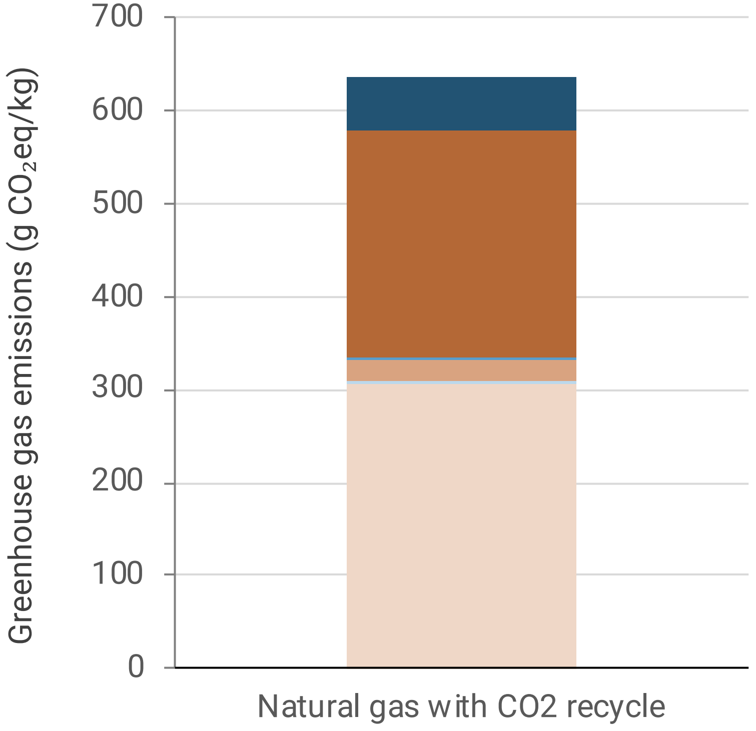
Methanol from natural gas with CO_2 recirculation
Supply chain emissions



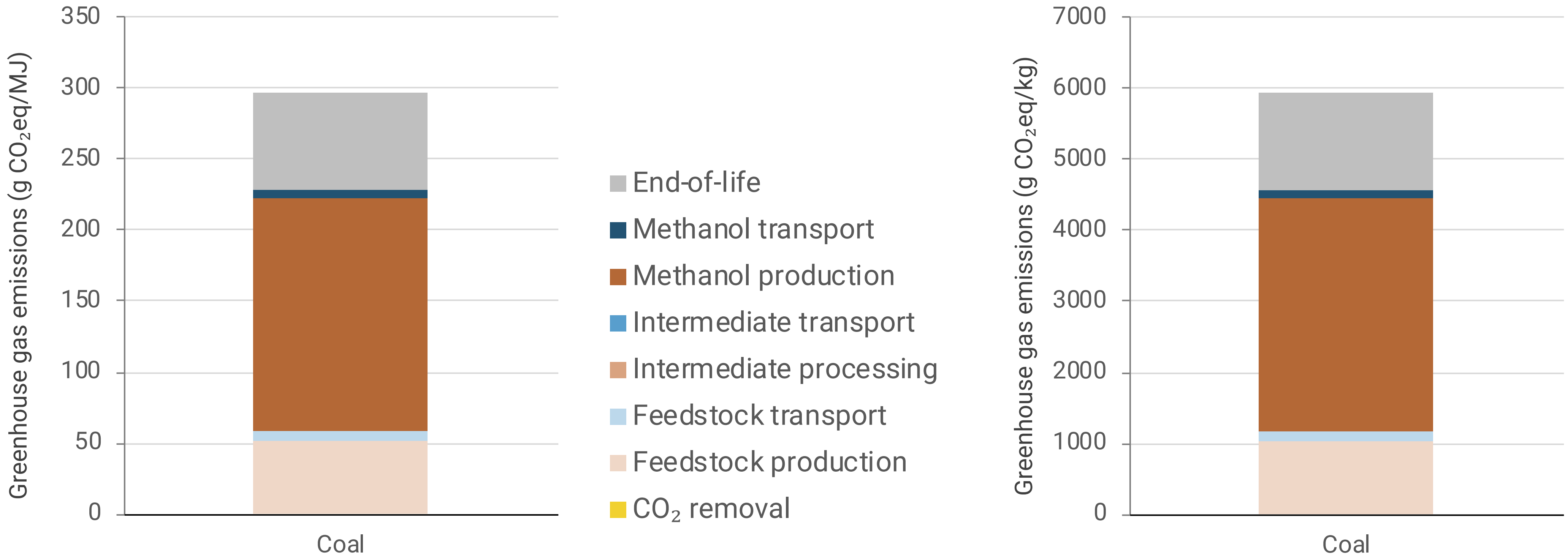


- Several methanol production facilities apply CO_2 recirculation to further increase methanol production. At the same time this consumes CO_2 that would otherwise be vented. The combined effect (less emissions from the facility, divided over more product) of a 10% increase in methanol production (as observed in one installation) can therefore reduce the lifecycle carbon footprint with about 10 g/MJ.

- If both the upstream emissions from natural gas supply are reduced (discussed on the previous slide) and CO_2 recirculation is applied, methanol could have a carbon footprint of around about 93 g CO_2eq/MJ (25 g CO_2eq/MJ upstream emissions + 69 g from combustion)

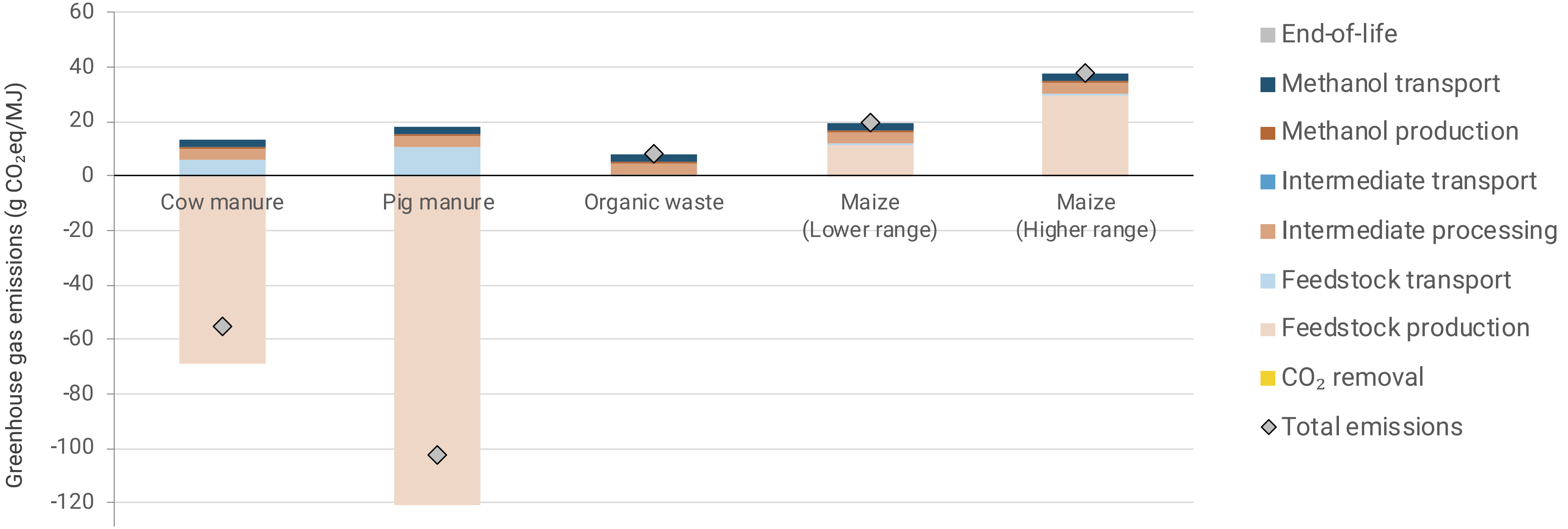
- Note that the scope for applying CO_2 recirculation within existing facilities is limited by reactor sizes and other bottlenecks throughout the entire installation.

Methanol from coal
Full lifecycle emissions



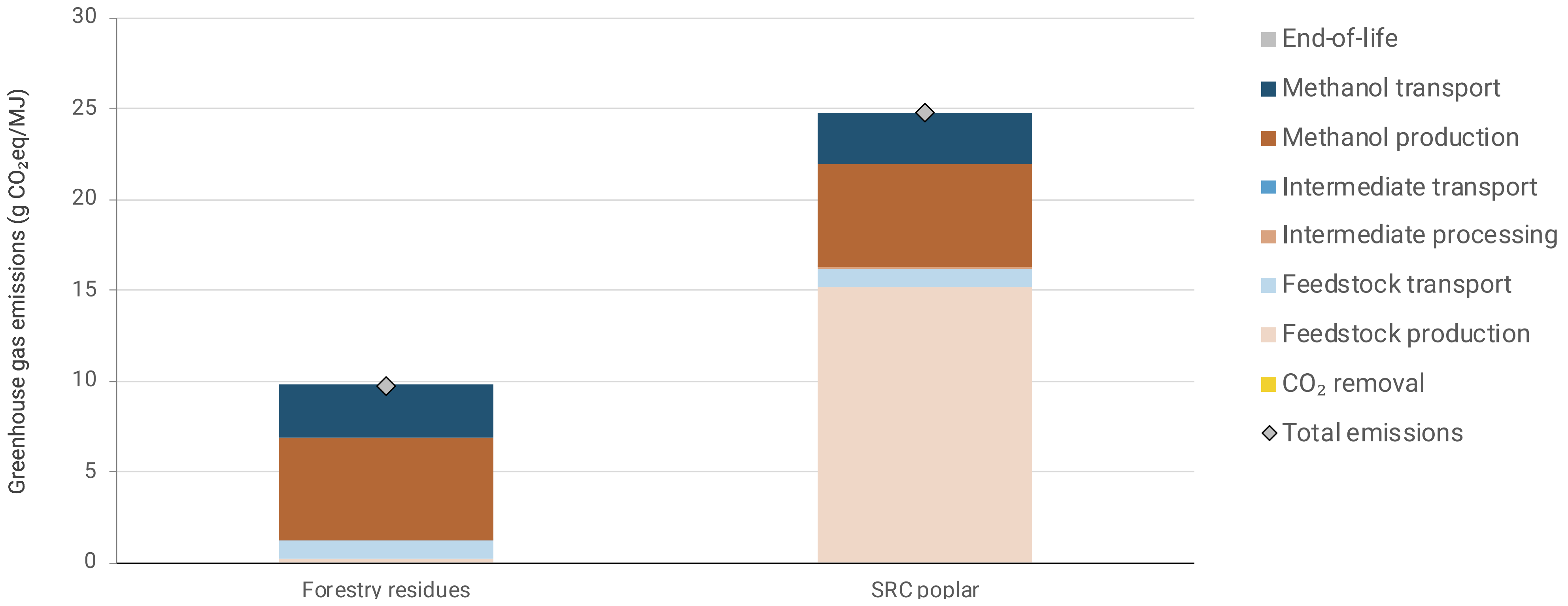
- The carbon footprint of methanol produced from coal is nearly 300 g CO_2eq/MJ, which is about 3 times higher than that of natural gas based methanol.
- The supply chain emissions mainly originate from the conversion facility, and also the mining, washing and selection of coal causes significant carbon impacts. We assume that significant improvements are possible in the conversion process, via CO_2 recirculation as is observed in natural gas based facilities, but we found no information about such technological improvement options for coal.
- The end-use emissions are (stoichiometrically) the same as for all fossil based methanol, namely 69 g CO_2eq/MJ.

Methanol from biomethane
Supply chain emissions depend on feedstock



- 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_2eq/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 feasible 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_2eq/MJ manure or 54 kg CO_2eq/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 feedstock component of the biomethanol is in all cases about 1.6 – 1.8 times larger than that of the biomethane intermediate product.
- For maize the bandwidth of results relates to variations in the cropping system, crop yields, and in the amount and application of fertiliser.

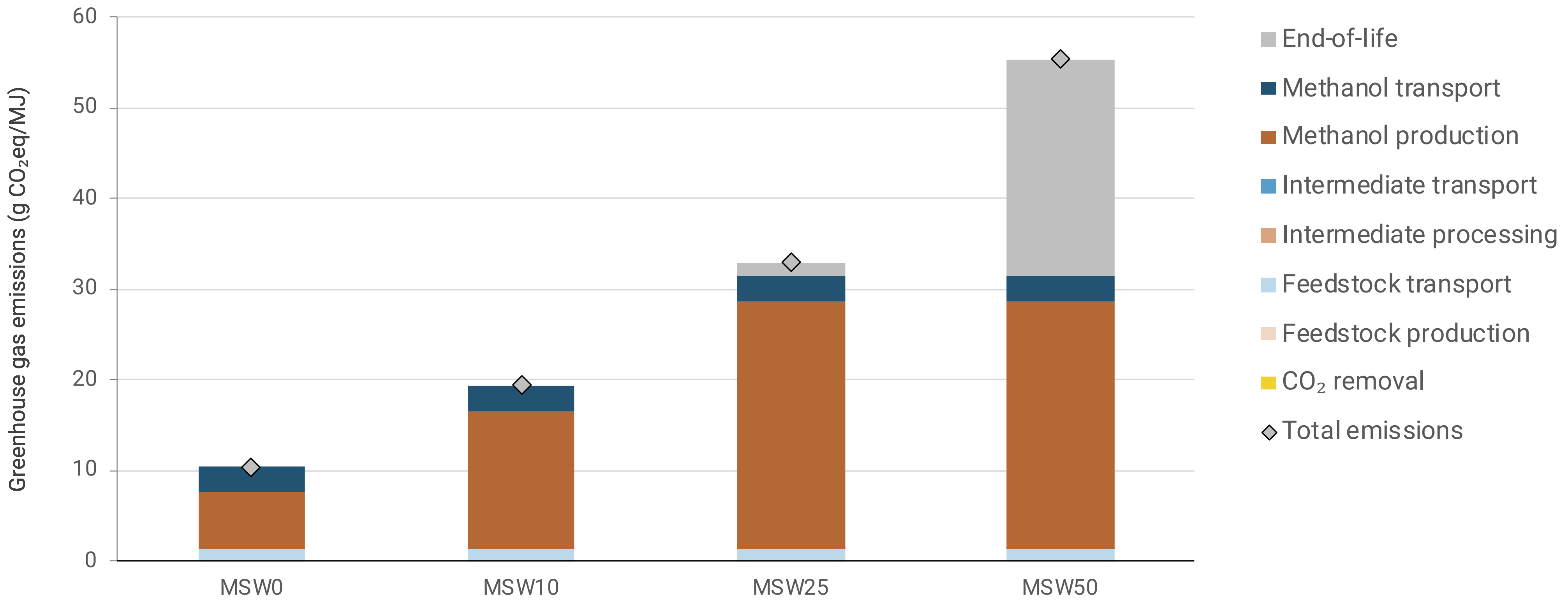
Methanol from wood
Supply chain emissions depend on type of biomass



- Methanol produced from wood has a carbon footprint between 10 and 20 g CO_2eq/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 require 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 2017].
- Emissions of the methanol production are associated with the consumption of natural gas (as defined in the natural gas pathway) and electricity (wind power).

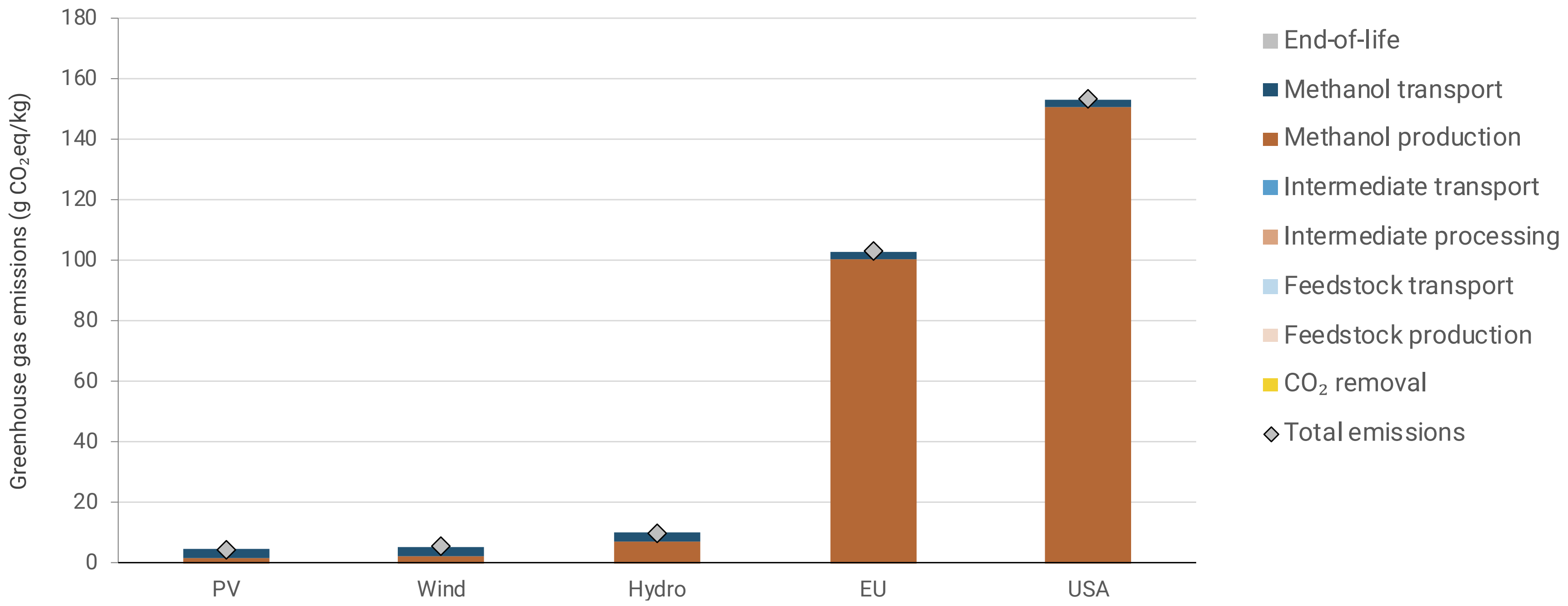
[EC JRC 2017 Solid and gaseous bioenergy pathways: input values and GHG emissions]

Methanol from municipal solid waste
Supply chain emissions depend on share recyclable



- Methanol produced from municipal solid waste (MSW) has a carbon footprint of 10-55 g CO_2eq/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_2eq/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 (because we try to allocate the least climate emissions to the final product, see Page 43), and then the emissions from end-use increase when moving to 10%, 25% or 50% non-climate neutral carbon in the MSW.

e-methanol
Supply chain emissions depend on source of electricity



- 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. The climate neutrality of CO_2 is discussed in more detail on Page 55.
- When the hydrogen is produced from solar PV electricity, the lifecycle carbon footprint of e-methanol can be small, about 4.4 g CO_2eq/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_2eq/kWh, the lifecycle carbon footprint becomes >100 g CO_2eq/MJ, which means that the emissions would be higher than for methanol from natural gas.

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Annex 1
Approach

Approach
Methanol producers provided company pathway specific data

Company involvement

- The data for the carbon footprint assessments in this study is based on data received from industry.
- The Methanol Institute provided contact information at 47 companies. These were contacted and motivated to participate.
- Eventually, 12 respondents provided data on their installation. The companies involved represent the following feedstocks and pathways
    - 4 based on natural gas (some with carbon capture and storage of exhaust CO_2)
    - 1 based on natural gas supplemented with captured CO_2
    - 1 based on hydrogen via electrolysis + captured CO_2 from industry
    - 3 based on hydrogen via electrolysis + biomass for CO_2
    - 1 based on biomass
    - 1 based on biomass and municipal solid waste
    - 1 based on an industrial waste stream
- About half of the companies involved are currently producing, the remaining companies are planning to produce within 2-5 years, and their facilities are in different stages of development. The level of detail of data received varied per respondent.
- We made limited judgement on the quality of the data received. Mass and energy balances were checked, and were found to be be realistic. Data on similar pathways was cross-checked. The economic feasibility of future installations was not judged.
- The data obtained from the participating companies is (in most cases) provided on a confidential basis. Therefore, the pathways and their results in the present overview report are based on aggregated data and anonymised results.

Development of individual companies reports

- All participating companies receive a report specifically for their installation, detailing all input, parameters and methodological considerations, results, variations and discussion.
- The individual company data and reports are confidential, and not shared with Methanol Institute or third parties.
- At the time of writing, 8 reports are completed with review pending, the 4 remaining are close to completion.

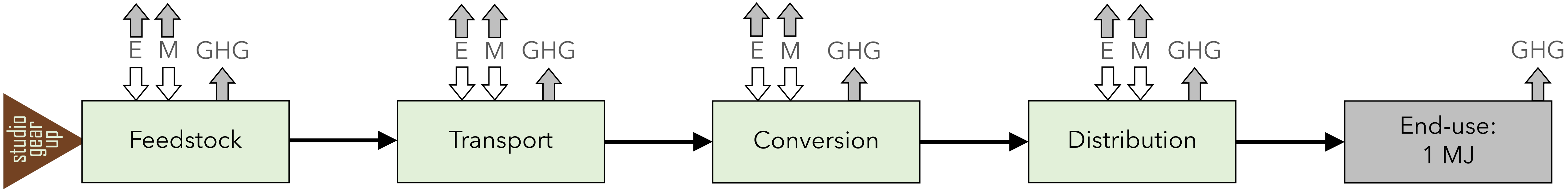
Data for coal and biomethane production pathways

- The present report also contains results for methanol from coal and from biomethane. Data for this was not supplied by the respondents and was developed on basis of literature.

Annex 2
Modelling parameters

Overview

- Inventory is taken of energy and material use in every step of the supply chain.
- Energy and material use lead to greenhouse gas emissions. Material loss can also lead to greenhouse gas emissions. End-use emissions are only considered for fossil based methanol.
- This annex includes all parameters used in the assessment of the pathways.
- First, for each of the pathways, feedstock production, transport and conversion to methanol are characterised:
  - Methanol from natural gas (Pages 24-30)
  - Methanol from coal (Pages 31-33)
  - Methanol from biomethane from anaerobic digestion of various crops and waste streams (Pages 34-37)
  - Methanol from solid biomass (Pages 38-40)
  - Methanol from municipal solid waste (Pages 41-43)
  - Methanol from (renewable) electricity and CO_2 captured from other installations (Pages 44-48)
- On Page 49, distribution or transport to end-use is characterised.
- The full methodology is explained in Annex 3.



Pathway 1 - Methanol from natural gas

Natural gas production and transport

Natural gas

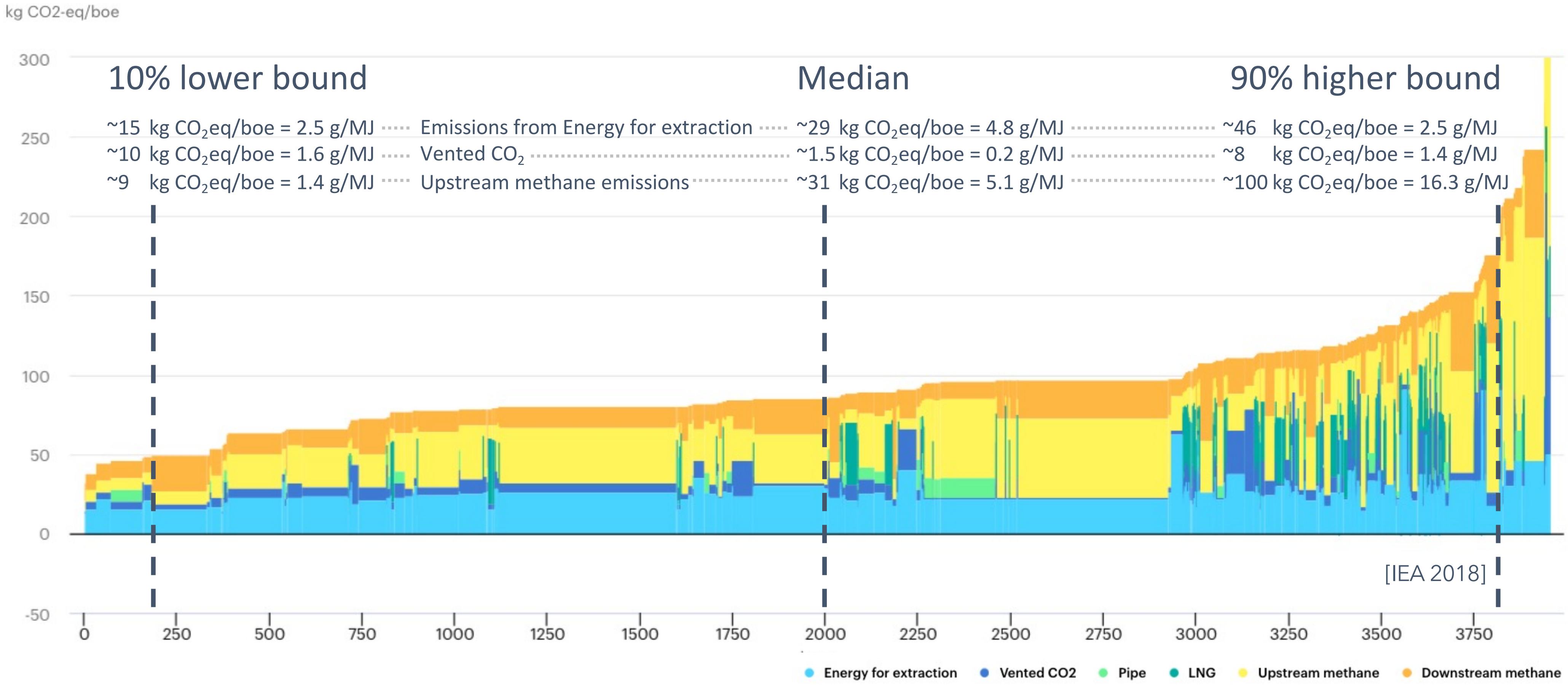
- Natural gas is extracted from wells, upgraded, and assumed to be transported over 100 km via gas grid.
- We have assumed a North American natural gas quality [Enbridge 2021] with density of 0.58 kg/Nm^3, Lower Heating Value is 38.8 MJ/kg, carbon content of 0.744 g/g, and (consequently) end-of-life emissions of 2.73 kg CO_2/kg natural gas.
- IEA provides an overview of emissions from natural gas production and supply worldwide. On average, this leads to about 5 g CO_2eq/MJ natural gas emissions related to energy for extraction and 5 g CO_2eq/MJ natural gas from methane emissions at source [IEA 2018], see next page. Together this equals about 506 g CO_2eq/kg natural gas.
- For downstream emissions, we apply parameters from US practice. Emissions are mainly in the form of CO_2 and CH_4 from combustion exhaust and other venting from compressor systems [GREET 2020]:

	CH_4 leakage and venting	CH_4 flaring	CO_2 venting	Total emissions	Total gas loss
Natural gas extraction and source methane emissions				506 g CO_2eq/kg	~10%
Transmission	46.9 gCO_2eq/tonne.km	-	-		0.0047% / km
Intermediate processing	6.9 gCO_2eq/kg natural gas	9.2 gCO_2eq/kg natural gas	23.5 gCO_2eq/kg natural gas		2.7%

[Enbridge 2021, Chemical composition of natural gas (from supply basins in western Canada, the United States and Ontario producers) | IEA 2018, Spectrum of the well-to-tank emissions intensity of global gas production | GREET 2020, GREET 1 Series (Fuel-Cycle Model) Rev1 | EEA 2019. European Environment Agency, Greenhouse gas emission intensity of electricity generation for 2019]

Upstream emissions from natural gas

- IEA reported the greenhouse gas intensity of natural gas around the world [IEA 2018]
- As an average performance, we have taken the median of this graph and only considered the emissions due to energy for extraction (light blue), vented CO_2 (dark blue) and upstream methane emissions (yellow).
- Pipeline emissions and downstream methane emissions are taken from EPA as discussed on the previous slide.
- IEA also shows how emissions from oil and natural gas operations can be reduced with almost 50% by 2030 compared to 2018 [IEA 2020]



[IEA 2018, Spectrum of the well-to-tank emissions intensity of global gas production | IEA 2020 Methane tracker report]

Pathway 1 - Methanol from natural gas

Generic flowchart for the conversion facility

- For all pathways, the inputs to and products from the conversion facility need to be understood. A generic flow chart (valid for all pathways) is presented below.
- The amount and quality of information available differs between the pathways.

Pathway 1 - Methanol from natural gas

Mass and energy balance of the methanol production facility

- The mass and energy balances in the table below are all per year, and based on an annual output of 1,000,000 tonne methanol.
- The data is based on an average of several state-of-the art methanol production facilities included in the study.
- The average carbon efficiency (carbon in methanol output / carbon in natural gas input) is 78.0% in a range from 72.2% to 83.7%.
- The carbon dioxide emission is calculated from the carbon balance (next page).

Item	Unit	Input	Output
Natural gas	tonne	646,142	
Water	tonne	918,812	
Oxygen (as air)	tonne	194,867	
Electricity	GWh	42	
Methanol	tonne		1,000,000
Carbon dioxide	tonne		387,677
Waste water	tonne		12,808

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Pathway 1 - Methanol from natural gas
Carbon balance of the installation and process CO_2 emissions

- For all feedstock and products, the amount of carbon is calculated. Each tonne of C delivers $^{44}/_{12}$ tonne of CO_2.
- The difference between input and output, i.e. the balance of carbon, is assumed to leave the installation as CO_2 process emissions.
- CO_2 emissions mainly reside in stack emissions, while a relatively smaller volume occurs from wastewater treatment.
- Natural gas is assumed to contain 0.744 g carbon / g natural gas as an average of European gas composition.

Item	Unit	Input	Output
Carbon in natural gas	tonne C/year	480,730	
Carbon in methanol	tonne C/year		375,000
Total	**tonne C/year**	**480,730**	**375,000**
Balance	tonne C/year		105,730
Process emissions	tonne CO_2/year		387,677

Pathway 1 - Methanol from natural gas *with CO_2 recirculation*

Mass and energy balance of the methanol production facility

- After methane reforming, a surplus of hydrogen exists which is usually combusted in the facility boilers. When CO_2 rich flue gas is recirculated back into the methanol reactor, and reacts with this surplus hydrogen after methane reforming, the methanol production can be increased with 10% (observed in one facility). Therefore, the mass and energy balances in the table below (per year) assume a 10% higher methanol yield than in facilities without CO_2 recirculating.
- We furthermore assume the same inputs of water, oxygen and power consumption, and waste water production as in the case without recirculation (based on the average of multiple state-of-the-art natural gas based methanol production facilities).

Item	Unit	Input	Output
Natural gas	tonne	646,142	
Water	tonne	918,812	
Oxygen (as air)	tonne	194,867	
Electricity	GWh	42	
Methanol	tonne		1,100,000
Carbon dioxide	tonne		271,295
Steam / waste water	tonne		12,808

Pathway 1 - Methanol from natural gas *with CO_2 recirculation*

Carbon balance of the installation and process CO_2 emissions

- For all feedstock and products, the amount of carbon is calculated. Each tonne of C delivers $^{44}/_{12}$ tonne of CO_2.
- The difference between input and output, i.e. the balance of carbon, is assumed to leave the installation as CO_2 process emissions.
- CO_2 emissions mainly reside in stack emissions, while a relatively smaller volume occurs from wastewater treatment.
- Natural gas is assumed to contain 0.744 g carbon / g natural gas as an average of European gas composition.

Item	Unit	Input	Output
Carbon in natural gas	tonne C/year	480,730	
Carbon in methanol	tonne C/year		412,500
Total	**tonne C/year**	**480,730**	**412,500**
Balance	tonne C/year		68,229
Process emissions	tonne CO_2/year		250,173

Pathway 2 – Methanol from coal

Coal production and transport

Coal production

- 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 [Luo 2017].
- Carbon emissions from mining (400 m depth) concern coalbed carbon leaks and emissions from energy use. About 2.72% of the raw coal is consumed in heating boilers. Mining equipment consumes about 33.7 kWh electricity per tonne, with a carbon intensity of 855 g CO_2eq/kWh.
- Coal selection and washing consumes a small amount of electricity (3 kWh/tonne) and some spontaneous combustion can occur (1%).
- 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, with an end-of-life emission of 1.98 kg CO_2/kg coal.

Coal transport

- 75% of the coal is transported by truck over 387 km (2.77 MJ/tonne/km) while 25% is transported by diesel locomotive over 165 km (0.105 MJ/tonne/km). Diesel lifecycle emissions are 95.1 g CO_2eq/MJ [JRC 2017]. We assume that 1% of coal is lost during transport.

	CH_4 leakage	CO_2 leakage / emission	Total coal loss
Coalbed carbon leak	469 gCO_2eq/kg coal	20 g CO_2eq/kg coal	
Coal consumption in heating boilers		53.8 g CO_2eq/kg coal	2.72% of raw coal
Electricity consumption by mining equipment		28.8 g CO_2eq/kg coal	
Spontaneous coal combustion		19.8 g CO_2eq/kg coal	1% of raw coal
Electricity consumption in selection/washing		2.6 g CO_2eq/kg coal	
Transport by truck (diesel)		263 g CO_2eq/tonne.km	
Transport by rail (diesel)		10.0 g CO_2eq/tonne.km	

[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]

Pathway 2 - Methanol from coal
Mass and energy balance of the methanol production facility

- The analysis of methanol from coal, and the parameters as presented below, are based on a case study of methanol from bituminous coal, including gasification, water gas shift, methanol synthesis and rectification [NPCPI 2017]. Input and output are per year, based on an output of 600,000 tonne/year methanol and 8,000 hours/year operation time.
- The facility emits carbon dioxide via purge gas and acid gas. The amount of fuel gas is estimated by combining NPCPI data on the amount of carbon with the assumption that half of the carbon originates from carbon monoxide and half from methane.
- The facility also produces waste water and gasification slag. The carbon content of these streams is given in the NPCPI study, and is relevant for the carbon balance on the following page, but the total volume of the stream is unknown. The consumption of water and oxygen intake is also unknown.
- The input of other consumables is also unknown – the impact of these on the final result is estimated to be low [for instance about 0.1% of the total emissions in Śliwińska 2017] and further ignored.

Item	Unit	Input	Output
Coal	tonne	834,783	
Coal for heat		173,123	
Electricity	GWh	440	
Methanol	tonne		600,000
Fuel gas	tonne		4,800
Gasification slag, waste water	tonne		unknown
Carbon dioxide	tonne		1,588,910

[NPCPI 2017, Status quo and coping strategies for carbon emission in nitrogen fertilizer and methanol industries | Śliwińska 2017, Environmental life cycle assessment of methanol and electricity co-production system based on coal gasification technology]

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Pathway 2 - Methanol from coal

Carbon balance of the installation and process CO_2 emissions

- For all feedstock and products, the amount of carbon is calculated.
- The coal is assumed to contain 0.69 g carbon / g coal for bituminous coal.
- The difference between input and output, i.e. the balance of carbon, is assumed to leave the installation as CO_2 process emissions.
- CO_2 emissions mainly reside in stack emissions, while a relatively smaller volume occurs from wastewater treatment.
- Carbon in fuel gas leaves the installation as a useful product. Carbon in gasification slag is assumed to be sequestered for longer time.

Item	Unit	Input	Output
Carbon in coal	tonne C/year	695,455	
Carbon in methanol	tonne C/year		225,000
Carbon in fuel gas	tonne C/year		2,616
Carbon in slag	tonne C/year		34,500
Total	**tonne C/year**	**695,455**	**262,116**
Balance	tonne C/year		433,339
Process emissions	tonne CO_2/year		1,588,910

Pathway 3 - Methanol from biomethane from anaerobic digestion
Emissions from production of various feedstocks

Item	Unit	Value	Comment
Cow manure	g CO_2eq/kg	-54	• Bonus according to RED II Annex VI.B.1.(b)
Pig manure	g CO_2eq/kg	-54	• Bonus according to RED II Annex VI.B.1.(b)
Organic waste	g CO_2eq/kg	0	• Waste has zero emissions by definition
Maize silage (low range)	g CO_2eq/kg	77	• See discussion below
Maize silage (high range)	g CO_2eq/kg	200	• See discussion below

- The Renewable Energy Directive awards a bonus for the processing of manure, of 45 g/MJ or 54 g/kg fresh manure.
  - In the calculations, we have applied a flat factor of 54 g/kg fresh manure. Since the calorific value varies between source (animal, location), the 54 g/kg can be far too high or far too low. It would be better to calculate with the 45 g/MJ, but the calorific value related is often unknown.
  - The calorific value is probably a proxy for the gas yield (next page). Calculations should be improved by ensuring the bonus is in line with the calorific value and the biomethane yield (and that it represents the methane that would be emitted autonomously).
- Strong differences in the carbon footprint of maize exist between literature sources. Performance will differ per plot and depends mainly on the fertiliser input and the crop output. Note that both maize grains and maize silage are used in anaerobic digesters the carbon footprint of the feedstock. The data in the table relate to maize silage:
  - GREET 2021 reports 87.2 g CO_2eq/kg. It is unclear whether this concerns maize grains or maize silage.
  - Biograce reports 295.3 g CO_2eq/kg, based on a very low maize grain yield of 3.88 tonne/ha, where 9 tonne/ha is achievable. This is not silage!
  - 140 – 290 g CO_2eq/kg with a mean of 200 g CO2eq/kg for maize silage produced in five USA States [Adom 2011]
  - 188 g CO_2eq/kg for maize silage in New Zealand [Ledgard 2015]
  - 77 g/ CO_2eq/kg for maize silage on basis of Dutch maize silage [Blonk 2015]
  - In a low-tillage system, the carbon footprint could be as low as 40 g CO_2eq/kg for maize grain [Holka 2020] and likely lower for maize silage.

[Adom 2012, Regional carbon footprint analysis of dairy feeds for milk production in the USA | Ledgard 2015, Total greenhouse gas emissions from farm systems with increasing use of supplementary feeds across different regions of New Zealand | Blonk 2015, Agri-footprint 2.0 Part 2 Description of data | Holka 2020 Carbon footprint and life-cycle costs of maize Production in conventional and non-inversion tillage systems]

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Pathway 3 - Methanol from biomethane from anaerobic digestion
Raw feedstock transport

Feedstock transport

- Raw feedstock (crops, manure or organic waste) is assumed to be transported for 50 km by truck. The emission factor for transport by road truck is 95.9 g CO_2eq/tonne.km (based on 1.01 MJ/tonne/km fuel consumption for a road truck carrying liquids [Biograce 2015], and 95.1 g CO_2eq/MJ lifecycle emissions [JRC 2017]).
- During transport, handling and storage, material may be lost due to process technical inefficiencies, spills and biological degradation. The extent of losses depends on many factors, and could be up to 8% of the dry mass. Because of the local sourcing, we assume that losses during transport and handling are limited to 2%.

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[Biograce 2015, Version 4d for Compliance | JRC 2017, Definition of input data to assess GHG default emissions from biofuels in EU legislation]

Pathway 3 - Methanol from biomethane from anaerobic digestion
Biomethane production and transport

Biomethane production via anaerobic digestion

- In the carbon footprint calculation, one must ensure that the same product is considered for the feedstock carbon footprint and the biomethane yield. For instance, the crop yield for maize silage (up to 30 tonne/ha) is much higher than for maize grains (up to 9 tonne/ha), and maize silage therefore has a lower carbon footprint. However, the biomethane yield from maize silage (301 Nm^3/tonne) in turn is lower than from maize grains (up to 605 Nm^3/tonne) [Hutňan 2009], which (partially) reduces the advantage.

Item	Unit	Value	Comment
Cow manure	Nm^3/tonne	35	
Pig manure	Nm^3/tonne	20	
Organic waste	Nm^3/tonne	300	
Maize silage	Nm^3/tonne	300	

Biomethane transport

- Biomethane transport is assumed to be 100 km via the natural gas grid. Energy consumption, product loss and emissions are taken the same as for natural gas transport (Page 24).

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[Biograce 2015, Version 4d for Compliance | JRC 2017, Definition of input data to assess GHG default emissions from biofuels in EU legislation | Hutňan 2009, Biogas production from maize grains and maize silage]

Pathway 3 - Methanol from biomethane from anaerobic digestion
Mass and energy balance of the methanol production facility

Biomethanol production

- Biomethane is assumed to be processed in a state-of-the-art natural gas based biomethanol production facility.
- The mass and energy balance of the methanol production facility is therefore equal to the pathway based on natural gas, again assuming a carbon efficiency of 78.0% (Pages 27-28).

Pathway 4 - Methanol from solid biomass

Feedstock production and transport

Forest residues

- Wood has a short carbon cycle. The CO_2 emission during combustion is equal to the CO_2 uptake during the growth of the biomass and therefore they cancel out. Depending on the type of wood, the landscape and management practice, the carbon balance can be settled within decades, and energy from wood can be regarded climate neutral. Note that this requires sustainable supply chain management.
- We assume the biomass pathways are based on forest residues, which are assumed to be climate neutral, because these residues are unavoidable in forestry. The end-of-life emissions of methanol produced from these residues are therefore zero.
- Energy and material use along the supply chain can still cause emissions. Residues, by definition, have no upstream climate impacts before the point they are residues. Collection of the residues usually leads to some emissions. These emissions are small and usually ignored in lifecycle assessment.
- We assume that the forest residues that enter the methanol production facility have a moisture content of 30% and are further dried/pre-treated within the facility. We assume the forest residues during the full transport contain the same 30% moisture.
- Biomass usually contains between 45% and 50% (by mass) of carbon on a dry matter basis, we therefore take 47.5% carbon [FAO 2005].

Feedstock transport

- The forest residues are assumed to be transported over 100 km by truck on average. The emission factor for transport by road truck is 95.9 g CO_2eq/tonne.km (based on 1.01 MJ/tonne/km fuel consumption for a road truck carrying liquids [Biograce 2015], and 95.1 g CO_2eq/MJ lifecycle emissions [JRC 2017]).
- During transport, handling and storage, material may be lost due to process technical inefficiencies, spills and biological degradation. The extent of losses depends on many factors, and could be up to 8% of the dry mass in the case of wood chips, but lower for stems (larger chunks) or pellets (treated) [Bioboost 2013]. Due to the transportation distance and the nature of the material, we assume that losses during transport and handling are 4%.

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[FAO 2005, Carbon Content of Vegetation | Biograce 2015, Version 4d for Compliance | JRC 2017, Definition of input data to assess GHG default emissions from biofuels in EU legislation | Bioboost 2013, Logistics processes for transport, handling and storage of biomass residues from feedstock sources to decentral conversion plants (report D1.4)]

Pathway 4 - Methanol from solid biomass
Mass and energy balance

- The mass and energy balances in the table below are per year and based on an annual output of 100,000 tonne methanol.
- The syngas after gasification is rich in hydrogen. To avoid loss of the valuable biogenic carbon, additional hydrogen is produced by an electrolyser integrated within the system boundaries. The inputs become demineralised water + electricity instead of oxygen and hydrogen.

Item	Unit	Input	Output
Forestry residues	tonne	200,000	
Natural gas	tonne	3,000	
Water	tonne	850,000	
Demineralised water	tonne	92,854	
Electricity (total) (wind)	GWh	720	
Methanol	tonne		100,000
Carbon dioxide	tonne		112,713

- The additional natural gas (for providing sufficient process heat) is assumed to be supplied from the same source and in the same manner as in the natural gas to methanol pathway (Page 24).

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Pathway 4 - Methanol from solid biomass
Carbon balance of the installation and process CO_2 emissions

- For all feedstock and products, the amount of carbon is calculated.
- The difference between input and output, i.e. the balance of carbon, is assumed to leave the installation as CO_2 process emissions CO_2 emissions mainly reside in stack emissions, while a relatively smaller volume may stem from wastewater treatment.
- Natural gas is assumed to contain 0.744 g carbon / g natural gas (see Page 24).
- Note that the process carbon emissions are partly climate neutral, as they stem from the biomass. The part that stems from the natural gas has a climate impact. Since the natural gas is used to drive the process, the emissions are allocated fully to the process. This implies that the methanol product remains fully climate neutral (in the end-use emissions).

Item	Unit	Input	Output
Carbon in forest residues	tonne C/year	66,500	
Carbon in natural gas	tonne C/year	2,232	
Carbon in methanol	tonne C/year		37,500
Total	**tonne C/year**	**68,732**	**37,500**
Balance	tonne C/year		31,232
Process carbon emissions	tonne CO_2/year		114,517
- of which have climate impact	tonne CO_2/year		8,184

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Pathway 5 - Methanol from municipal solid waste

Feedstock production and transport

Municipal solid waste

- Municipal solid waste includes an biogenic and non-biogenic part. We assume that municipal solid waste concerns only non-recyclable waste that would otherwise be landfilled. In that case, the end-of-life emissions of methanol produced from municipal solid waste are zero.

Notion on Recycled Carbon Fuels

- In the frame of the European Renewable Energy Directive methanol produced from non-recyclable waste counts as a Recycled Carbon Fuel (RCF). Note that the Directive explicitly states feedstock for RCFs should not be suitable for material recovery. Proof of this will have to be provided through certification.
- The Commission is expected to further clarify the sustainability requirements and carbon accounting methodology for RCF this year (2021). At the moment, none of the EU Member States have included RCF in their national legislation.
- Note that the definition of the waste part in municipal solid waste may change in the coming years, as the obligatory share of recycling is increasing – that part will may be available for RCF.

Composition

- We assume the biogenic part has a moisture content of 71.9% at the point of collection and that the dry matter has a a carbon content of 46.3% based on an average of observations for the organic fraction in MSW around the world [Paritosh 2018].
- We assume that half of the non-biogenic material concerns inorganic materials and the other half concerns fossil based plastics. In that case, the carbon content of the dry matter will be approximately 40%. We assume the moisture content to be about 10%.

Feedstock transport

- We assume that during transport the characteristics remain the same, except that about 5% of the material is lost.
- The municipal solid waste is transported 100 km by truck on average, with the same impact per km as for solid biomass.

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[Paritosh 2018, Fraction of municipal solid waste: Overview of treatment methodologies to enhance anaerobic biodegradability]

Pathway 5 - Methanol from municipal solid waste
Mass and energy balance

- The mass and energy balances in the table below are per year and based on an annual output of 100,000 tonne methanol.
- The syngas after gasification is rich in hydrogen. To avoid loss of the valuable biogenic carbon, additional hydrogen is produced by an electrolyser integrated within the system boundaries. The inputs become demineralised water + electricity instead of oxygen and hydrogen.

Item	Unit	Input	Output
Municipal solid waste	tonne	230,000	
Natural gas	tonne	3,450	
Water	tonne	850,000	
Demineralised water	tonne	92,854	
Electricity (total)	GWh	720	
Methanol	tonne		100,000
Carbon dioxide	tonne		49,354

- The additional natural gas (for providing sufficient process heat) is assumed to be supplied from the same source and in the same manner as in the natural gas to methanol pathway (Pages 24).

Pathway 5 - Methanol from municipal solid waste
Carbon balance of the installation and process CO_2 emissions

- For all feedstock and products, the amount of carbon is calculated.
- The difference between input and output, i.e. the balance of carbon, is assumed to leave the installation as CO_2 process emissions CO_2 emissions mainly reside in stack emissions, while a relatively smaller volume may stem from wastewater treatment.
- Natural gas is assumed to contain 0.744 g carbon / g natural gas (see Page 24).
- Note that the process carbon emissions may be partly climate neutral, when they stem from the biogenic part of the waste, or if they stem from non-recyclable carbon. The part that stems from the natural gas and the part that stems from recyclable carbon in the feedstock, has a climate impact. The climate neutral emissions are first allocated to the end-use. If a larger part of the carbon is climate neutral, then this reduces the net emissions from the process.
- Since the natural gas is used to drive the process, its emissions are allocated fully to the process.

Item	Unit	Input	Output
Carbon in forest residues	tonne C/year	48,959	
Carbon in natural gas	tonne C/year	2,567	
Carbon in methanol	tonne C/year		37,500
Total	**tonne C/year**	**51,526**	**37,500**
Balance	tonne C/year		14,026
Process carbon emissions	tonne CO_2/year		51,429
- of which have climate impact	tonne CO_2/year		see discussion in text

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Pathway 6 - Methanol from renewable electricity
Mass and energy balance

- The mass and energy balances in the table below are per year and based on an annual output of 75,000 tonne methanol.

Item	Unit	Input	Output
Carbon dioxide	tonne	109,500	
Electricity (wind)	GWh	615	
Demineralised water	tonne	202,500	
Methanol	tonne		75,000
Hydrogen	tonne		1,570

Pathway 6 - Methanol from renewable electricity

Carbon balance of the installation and process CO_2 emissions

- For all feedstock and products, the amount of carbon is calculated
- The difference between input and output, i.e. the balance of carbon, is assumed to leave the installation as CO_2 process emissions (each tonne of C delivers $^{44}/_{12}$ tonne of CO_2)
- CO_2 emissions mainly reside in stack emissions, while a relatively smaller volume may stem from wastewater treatment.

Item	Unit	Input	Output
Carbon in CO_2 captured	tonne C/year	29,864	
Carbon in methanol	tonne C/year		28,125
Total	**tonne C/year**	**29,864**	**28,125**
Balance	tonne C/year		1,739
Process carbon emissions	tonne CO_2/year		6,375

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Generic electrolyser set-up
Feedstock

Water

- Electrolysers require 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.
- Demineralised water minimises this problem and its use in electrolysers is hence common practice. Due to higher upstream purification efforts, demineralised water has a higher greenhouse gas impact than conventional process water.
- Water electrolysis follows the electrochemical reaction:

$$2\ H_2O\ (l) \rightarrow 2\ H_2\ (g) + O_2\ (g)$$

- It follows from the respective molecular weights that every 9 kg of electrolysed water result in 1 kg of hydrogen and 8 kg of oxygen. The mass of hydrogen can better be calculated via the energy efficiency of the electrolyser (see below). The mass of oxygen is then calculated by multiplying the mass of hydrogen with a factor of 8.
- The water requirements are calculated via values provided from the manufacturer since the fraction of electrolysed water from the total water amount is unknown. Thyssenkrupp mentions a water consumption of < 1L per Nm^3 hydrogen [TK 2021]. In mass terms, this equates to 11.12 kg water per kg hydrogen. The difference to the stoichiometric minimum (11.12 – 9 = 2.12 kg water/kg hydrogen) is assumed to leave as waste water.

Electricity

- With current technology, electrolysers achieve energy efficiencies of about 66 % on a lower heating value (LHV) basis.
- For a hypothetical 25 MW_e electrolyser operating for 4,000 h/a (45 %) the electricity consumption of 100 GWh/a would result in 66 GWh/a hydrogen output (on a LHV basis). This is equivalent to 237.6 TJ/a. With hydrogen's LHV of 120 TJ/kt, this equates to 1.98 kt hydrogen per year.

[TK 2021, Thyssenkrupp Uhde Chlorine Engineers, Large-scale water electrolysis for green hydrogen production]

Generic electrolyser set-up
Flowchart

Inputs

Water
22,018 tonne/year
(1 L/Nm^3 hydrogen)

Electricity
100 GWh/year
(50 MW at 45 % use)

Conversion

Water electrolysis

η_{LHV} = 66 %

Outputs

Hydrogen
1,980 tonne/year

Oxygen
15,840 tonne/year

Waste water
4,198 tonne/year

Values between ( ) brackets are assumptions or literature values. **Bold** values are derived by studio Gear Up and used in the calculations.
Based on a hypothetical 50 MW$_e$ input facility running 4,000 operational hours per year.

Generic electrolyser set-up
Mass and energy balance

- The mass and energy balances in the table below are based on an annual output of 1,980 tonne hydrogen.

Item	Unit	Input	Output
Water	tonne	22,018	
Electricity	GWh	100	
Oxygen	tonne		15,840
Waste water	tonne		4,198
Hydrogen	tonne		1,980

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Methanol
Product transport

Methanol distribution to customers

For all the pathways assessed, we assume:

- 20 km by pipeline to port
- 5000 km by international bulk carrier

Impact factors for product transport

- Emission factor for pipeline transport is 15.74 g/tonne.km [Biograce 2015].
- The emission factor for international transport by ship bulk carrier is 11.3 g/tonne/km (based on 0.12 MJ/tonne/km fuel consumption for a product tanker [Biograce 2015], and 94.2 g CO_2eq/MJ lifecycle emissions [JRC 2017])

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[Biograce 2015, Version 4d for Compliance | JRC 2017, Definition of input data to assess GHG default emissions from biofuels in EU legislation]

Annex 3
Methodology

Methodology
Carbon footprint versus lifecycle analysis

Carbon footprint analysis
- In this project we calculated the carbon footprint of methanol from different feedstocks and via different production pathways
- A carbon footprint analysis considers all the greenhouse gas emissions from all the activities involved with:
  - The production or collection of feedstock
  - The transport of feedstock, intermediates, and final products
  - The conversion into intermediate and final products
  - The end-of-life fate of the final product (combustion in case of an energy product)
- This inclusion of all lifecycle steps is called well-to-wheel, well-to-wake or cradle-to-grave

Relation to lifecycle assessment (LCA)
- Carbon footprint analysis is only one category of lifecycle assessment (LCA)
- Carbon footprint analysis uses the accounting and computation methods of lifecycle assessment
- Lifecycle assessment usually covers many other (environmental) impacts that are "computable". It has a very wide impact scope (see box)
- In lifecycle assessment, impact categories can be weigthed to get a total impact score

Different names are used for the same analysis
- In broader LCA, carbon footprint is often called global warming, which puts more emphasis on the impact, and less on the carbon aspect
- In the EU Renewable Energy Directive it is called greenhouse gas impact
- In the US Argonne GREET model it is called carbon intensity
- Also, the carbon footprint of electricity is usually called carbon intensity

Life cycle assessment categories

- Global warming
- Ozone depletion
- Acidification of soil and water
- Eutrophication
- Photochemical ozone creation
- Depletion of abiotic resources – elements
- Depletion of abiotic resources – fossil fuels
- Human toxicity
- Fresh water aquatic ecotoxicity
- Marine aquatic ecotoxicity
- Terrestrial ecotoxicity
- Water pollution
- Air pollution

Methodology
Based on the Renewable Energy Directive

ISO principles 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 very different outcomes for the same supply chain or conversion pathway.

Method of current study

- The method applied in the current study is in line with the ISO guidelines, but it is more targeted to renewable fuels. The method is specifically based on Annex V of the EU Renewable Energy Directive (RED), which is intended for calculating the impact from biofuels to be sold as renewable fuels in the European market. The method is also directly useable to calculate the impact of fuels and energy products produced from other feedstock, including non-renewable feedstock.
- A key aspect of the RED methodology is that it treats co-products via energy allocation. Some other methods applied in the fuel domain, such as the US GREET model, use system expansion to account for co-products (see Page 57).

Methodology
Functional unit

Impact is expressed in CO_2 equivalent

- The carbon footprint calculations in this report thus 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.
- We use the Global Warming Potential (GWP) values for the 100-year time horizon from the IPCC 5th Assessment Report (AR5) as shown in the table. For instance, 1 gram of methane emission equals 28 gram CO_2 equivalent emission.

Common name	Chemical formula	Global Warming Potential GWP100
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265

Functional unit

- The impact is expressed in grams of CO_2 equivalent emission per amount of methanol delivered, more specifically mass (kg) or energy content (MJ). The energy is expressed as Lower Heating Value in line with the EU Renewable Energy Directive [EC 2018].
- The impact is thus expressed as g CO_2eq/kg, or g CO_2eq/MJ_{LHV}. To calculate from g/MJ to g/kg one multiplies with the Lower Heating value of 20 MJ_{LHV}/kg (according to the Renewable Energy Directive).

- The results in this main report are expressed for methanol delivered to the final customer.
- If the methanol is used in transport, for instance in shipping, sometimes the emissions are expressed per kilometre. This comparison may be interesting if the vehicle efficiency differs between the fuels and if one wants to demonstrate the efficiency gains. However, since all vehicles have different efficiencies, this also complicates the mutual comparison of (further chemical identical) methanol from different sources.
- Nevertheless, the calculations include the end-of-life stage of the methanol. Emissions from combusting methanol are included in the carbon footprint (see Page 54 on well-to-tank and well-to-wake).

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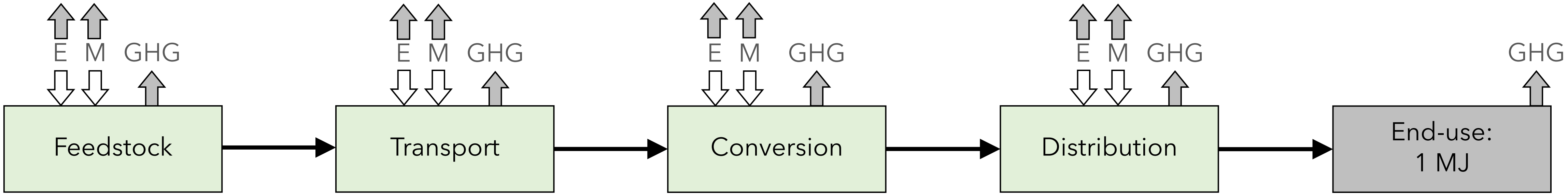
[EC 2018, Directive 2018/2001 on the promotion of the use of energy from renewable sources, Annex V.C]

Methodology
Complete lifecycle greenhouse gas emissions

Complete lifecycle
- The carbon footprint calculations include emissions from every stage of the supply and use of the methanol.
- This includes all emissions involved with the production and use of the energy and materials used in the supply chain, such as energy for feedstock production, fuels for transportation and materials consumed in the methanol production facility.
- It also includes the emissions from the end-of-life or end-use of the methanol, assuming that it is combusted (as a fuel).

- This approach is also called:
  - "Cradle-to-grave" for products with an end-of-life after functional use.
  - "Well to wheel" or "well to wake" for fuels that are used in a vehicle such as a ship or a car.

Inventory
- In practice, an inventory is made of all energy and material emissions and all the associated emissions that take place along a supply chain.
- The result is divided over the amount of product, so to understand the total emission per functional unit.



GHG = Greenhouse gases
= CO_2, CH_4, N_2O mainly
M = Materials
E = Energy

Methodology
End-use emissions

Stoichiometric emissions at end-use
- The physical emission at end-of-life is determined by the stoichiometry. It 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_{LHV}.

End-use emissions in the carbon footprint calculation
- For fossil-based methanol, such as from **natural gas** or **coal**, the combustion of methanol leads to a net CO_2 emission and this is accounted for. This emission from end-use often represents the largest share of emissions in the whole lifecycle.

- For methanol based on renewable sources, such as **biomass**, **biogas** or **the organic fraction of waste** the end-use emissions are climate neutral and therefore not counted. The carbon was previously absorbed from the atmosphere, during plant growth.
- When carbon is sourced from **direct air carbon capture** this also is the case.
- When carbon is **captured from another process** this avoided an earlier (and otherwise unavoidable) emission to 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 considered to be net climate neutral. 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 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.

Accounting for end-use emissions
- Even when we express the result per MJ, we assume that the methanol will be combusted

Well-to-tank emissions
- Some studies report only the well-to-tank emissions and exclude the end-use (tank-to-wake) emissions.
- This can be deceptive since it omits the end-use emissions which are the main differentiator between fossil and renewable methanol.

Well-to-wake or well-to-wheel emissions per km
- In some studies, the lifecycle emissions may be expressed per km, thus including the vehicle efficiency. This may be interesting on the level of an individual ship or car, but it limits the mutual comparison between fuels.

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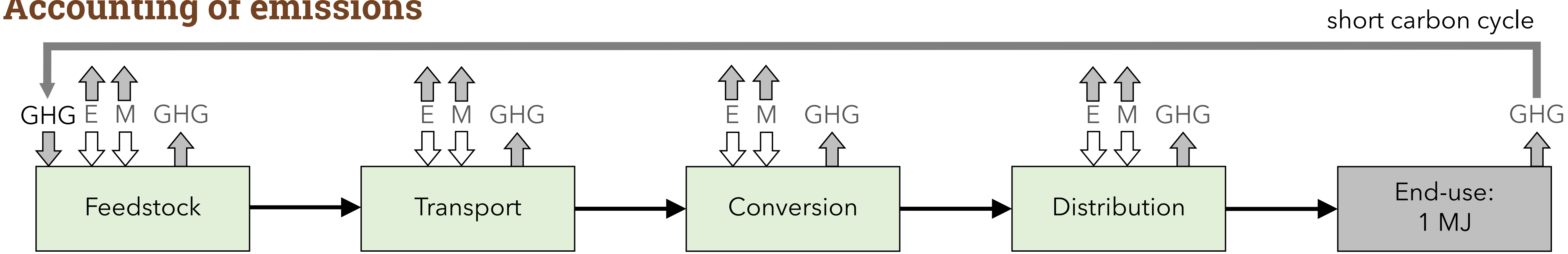
[EU 2018: The Renewable Energy Directive states that "credits from greenhouse gas emissions savings are given only once". This is relevant when CO_2 is captured from a biofuel production facility. If that facility already is credited for the capturing, then the CO_2 is no longer climate neutral. Otherwise, the savings would be double counted.]

Methodology
Accounting of emissions



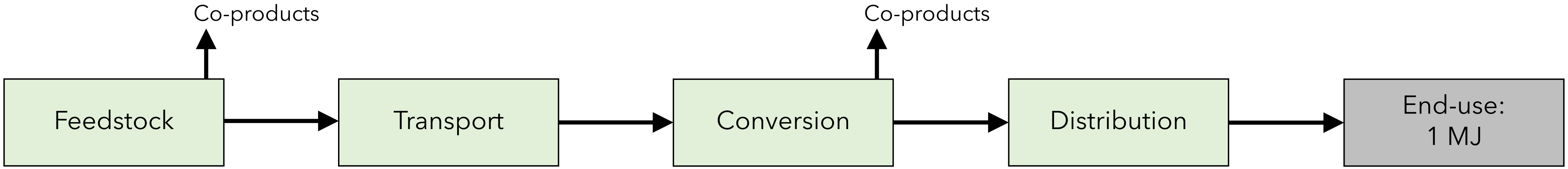
Accounting
- For each step, it is determined how much material passes through, to deliver 1 MJ of methanol at the end.
- For each step, it is then determined how much material and energy is used, and how much emissions are caused by these. Also, it it is determined how much direct emissions take place, for instance because of a natural process, a conversion process or a loss/slip of material.

- In the case of biomethanol, this for example could involve:
  - CO_2 emissions when fuel is being used in a tractor on the field or during transportation of feedstock/product, or when natural gas is being used in a conversion plant
  - N_2O emissions when fertiliser is being used on the field
  - CH_4 emissions in case of methane slip in an anaerobic digester
- At the end-use the stoechiometric CO_2 emissions are determined and it is judged how much of this is climate neutral.

The greenhouse gas emissions from processes supplying to the supply chain are also considered
- In the production of energy or materials that is used in the supply chain, for example:
  - During the exploration and refining of oil to deliver diesel for the tractor
  - The production of chemical fertiliser, or a catalyst that is used in the process
- Standard emission values are taken from databases and literature (to avoid endless modelling)

Capital goods are not included
- The production of "capital goods" such as the construction of a factory building, or the making of trucks, is not included.

Methodology
Example biofuel supply chain



Co-products carry away part of the (carbon) burden caused by the supply chains

In general lifecycle assessment, there are two approaches to account for co-products

- Substitution: Co-products from a biofuel chain avoid the production of same products elsewhere
  - Substitution is based on the **causality** principle
  - Approach: Credit by subtracting burden of avoided system
- Allocation: Most valuable products are most responsible for the environmental impact
  - Allocation is based on the **responsibility** for the action
  - Approach: Distribution of (upstream) burden over two or more products
- Both methods represent reality
  - Substitution is a more complicated methodology than allocation - and the results on basis of substitution differ in time and per location
  - Both methods inherently yield different results

Approach in the Renewable Energy Directive

- The Renewable Energy Directive prescribes energy allocation
- 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
- This means that every MJ of product (at a point where multiple products are created) has the same carbon footprint per MJ

Methodology
Land use emissions

Direct land use change

- When land use is changed for the supply of feedstock, this impacts the carbon stock in that land
- For instance, peat land is drained to grow trees, or grassland becomes cropland
- In the current study, for the supply chains involving biomass, direct land use change is not included

Indirect land use change

- When an existing cropland is being used, this cropland is no longer available for the original function
- This original function (crop) or may be supplemented by others elsewhere, and this may cause a loss of natural land elsewhere, which may cause carbon impacts
- Indirect emissions cannot be included in the current study since they cannot be observed or measured for individual supply chains. The indirect impacts from policies can be estimated at a regional or global level.

Annex 4

Carbon footprint of various maritime fuels

Carbon footprint for alternative maritime fuels
Well-to-tank and Tank-to-wake emissions according to ESSF

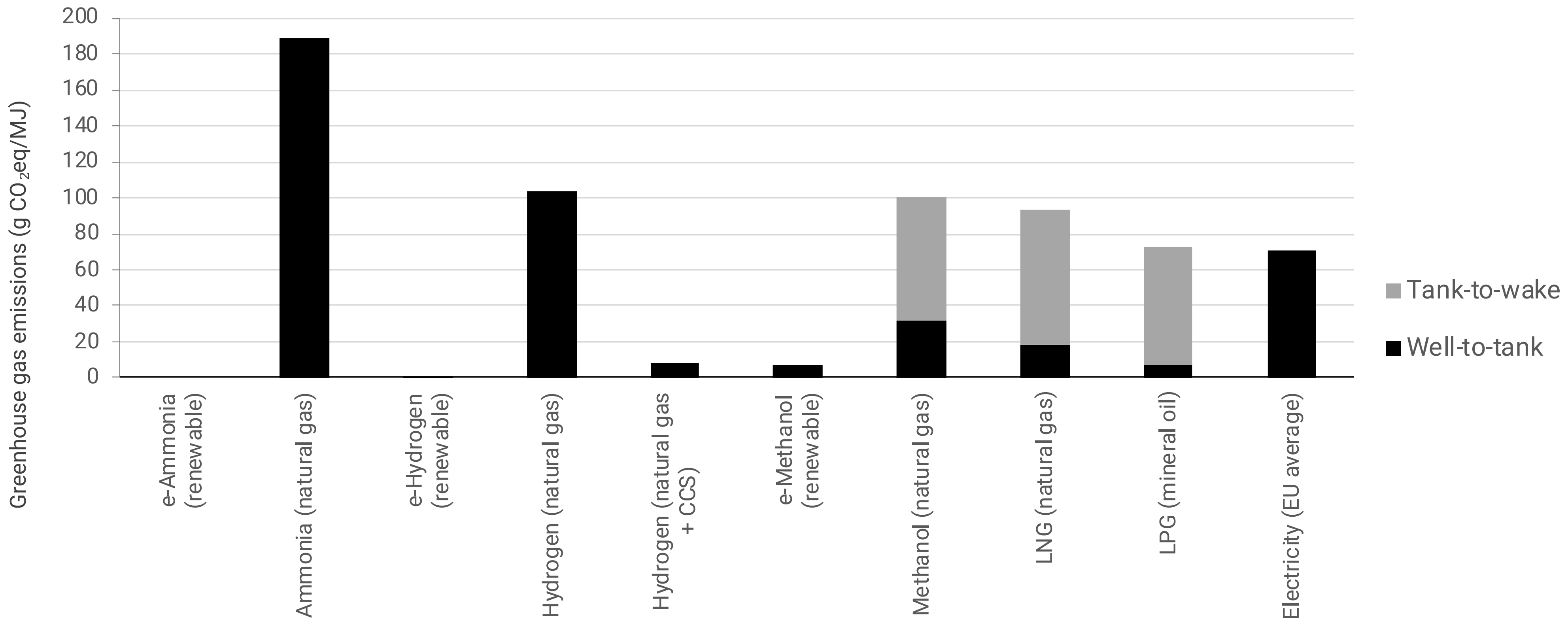
- Results from other studies are given for comparison. Methods may have differed and the outcomes are not per se comparable to the current study.

Fuel	Unit	Well-to-tank	Tank-to-wake	Well-to-wake	Source
e-Ammonia (renewable)	g CO_2eq/MJ	0	0	0	ESSF 2021
Ammonia (natural gas)	g CO_2eq/MJ	188.7	0	188.7	ESSF 2021
e-Hydrogen (renewable)	g CO_2eq/MJ	0.7	0	0.7	ESSF 2021
Hydrogen (natural gas)	g CO_2eq/MJ	103.9	0	103.9	ESSF 2021
Hydrogen (natural gas + CCS)	g CO_2eq/MJ	8.1	0	8.1	ESSF 2021
e-Methanol (renewable)	g CO_2eq/MJ	4 - 10	0	4 – 10	sGU 2021
Methanol (natural gas)	g CO_2eq/MJ	32	69	101	sGU 2021
LNG (natural gas)	g CO_2eq/MJ	18.4	75.1	93.5	ESSF 2021
LPG (mineral oil)	g CO_2eq/MJ	7.1	66.1	73.2	ESSF 2021
Electricity	g CO_2eq/MJ	70.8	0	70.8	EEA 2021

- Results for e-Methanol and methanol from natural gas have been taken from the current study. Note that the well-to-tank emission for methanol from natural gas has been taken as an average of the pathways presented on Page 11, such that the result either represents a regular facility with improved natural gas sourcing, or an average natural gas sourcing but with CO_2 recirculation in the methanol facility.
- Note that European Sustainable Shipping Forum (ESSF) applies (near) zero WTT emissions to e-fuels when produced from renewable energy. This is not correct, because solar PV has a carbon footprint of about 4 g CO_2eq/kWh, wind about 7 g CO_2eq/kWh and hydro about 19 gCO_2eq/kWh. Furthermore, conversion to e-fuels and transport to customer also involve greenhouse gas emissions.

[ESSF 2021, Database European Sustainable Shipping Forum | sGU 2021, studio Gear Up, Industry wide carbon footprint assessment study for Methanol Institute (this study) | EEA 2021, Greenhouse gas emission intensity of electricity generation]

Carbon footprint for alternative maritime fuels
According to ESSF



- See notes on previous page for sources and explanation.

Annex 5
Parameters in the JRC 2017 report

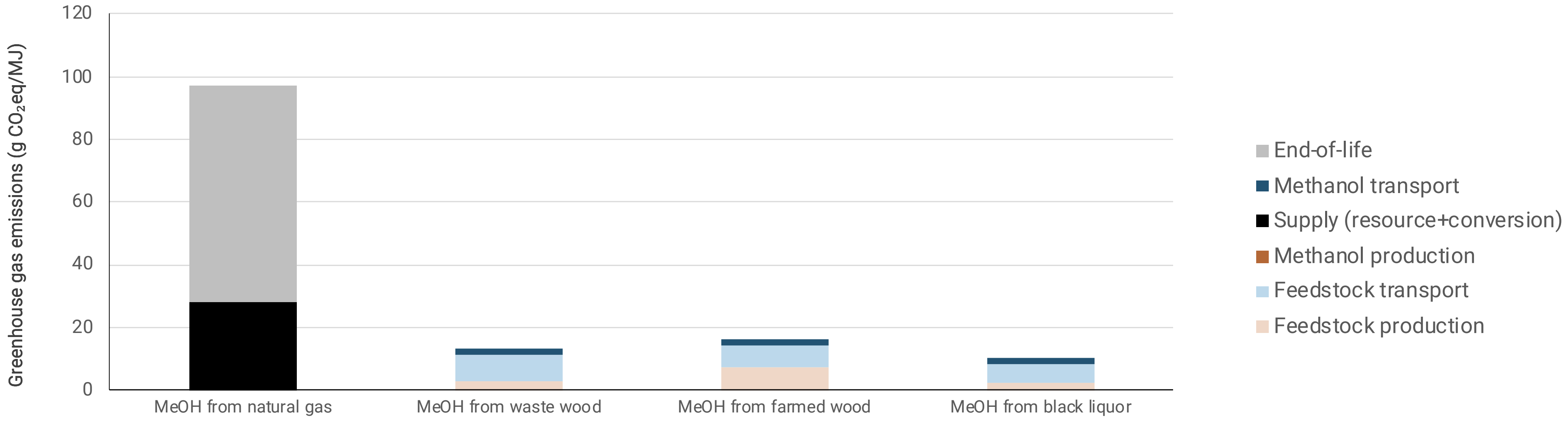
JRC report

- The default value for natural gas based methanol in EU legislation is explained in a study by JRC. The source data originates from a conference publication in 1998 [EC JRC 2017]. Since 1998, the conversion efficiency has improved, which both decreased the direct carbon emissions from methanol production facilities and slightly decrease the natural gas use (and therefore upstream emissions).
- We expected that emissions from natural gas based methanol production facilities would have decreased by now (2021) and that upstream emissions from natural gas sourcing would also have decreased.
- However, the current study shows actually an increase in upstream and facility emissions.
- We think this is caused by (1) the data in 1998 was based on a yet-to-be-build installation, and may have been too optimistic, (2) upstream emissions from natural gas sourcing were either underestimated, or related to better sourcing situations. In the current study, an average of global emissions is applied.

studio gear up

[EC JRC 2017 Definition of input data to assess GHG default emissions from biofuels in EU legislation]

Methanol supply chains in the JRC report



- The 2017 JRC report describes "… the assumptions made by the JRC when compiling the new updated data set used to calculate default and typical GHG emissions for the different biofuels pathways as proposed in the new RED-2 document." [JRC 2017].
- The report presents amongst others four pathways for the production of methanol, based on four feedstocks.
- Note that the supply chain elements addressed for biomethanol are more extensive than for natural gas based methanol.
- In biomethanol supply chains, the end-of-life emissions are zero because any CO_2 emission is biogenic (and therefore climate neutral). For the same reason the emissions from the production facility are also zero.

studio gear up

[EC JRC 2017 Definition of input data to assess GHG default emissions from biofuels in EU legislation]

2017 JRC
Data and sources

Pathway	Emissions (gCO_{2eq}/MJ final product)		Data sources for proces steps
Methanol from natural gas (as input in FAME production)	Supply Combustion	28.2 68.9	• Larsen 1998
Methanol from waste wood *(70% process efficiency)*	Cultivation Transport feedstock Processing Transport/distribution final	3.1 8.4 0.0 2.0	• Katofsky, 1993 • Dreier 1998 • Paisley 2001 • Atrax 1999
Methanol from farmed wood *(51% process efficiency)*	Cultivation Transport feedstock Processing Transport and distribution	7.6 6.6 0.0 2.0	• Same as for waste wood
Methanol from black liquor *(74% process efficiency from pulp)*	Cultivation Transport feedstock Processing Transport and distribution	2.5 5.9 0.0 2.0	• Berglin 1999 • Landälv 2007 • Ekbom 2005

- JRC 2017 based the carbon intensity calculation for natural gas based methanol on a single source.

studio gear up

JRC 2017
Literature overview

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