

FULL VALUE CHAIN GHG EMISSIONS OF INNOVATIVE TECHNOLOGIES IN INDUSTRY

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FULL VALUE CHAIN GHG EMISSIONS OF INNOVATIVE TECHNOLOGIES IN INDUSTRY

E-CRACKING, RENEWABLE AMMONIA FOR FERTILISER INDUSTRY, METHANOL VIA PLASTIC GASIFICATION & ETHYLENE USING LIGNOCELLULOSIC FEEDSTOCKS

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› PROJECT DETAILS

- **TNO project team**

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- **Client**

Ministry of Economic Affairs (EZK)

- **Project Duration**

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EXECUTIVE SUMMARY

› EXECUTIVE SUMMARY

- › The current policy instruments aim to reduce direct greenhouse gas (GHG) emissions of industrial processes (scope 1). Therefore, most industrial innovations target reducing scope 1 GHG emissions. While indirect GHG emissions related to the purchase of energy (Scope 2) are addressed through other policy instruments focusing on the energy sector, other indirect upstream and downstream GHG emissions, referred to as scope 3, are often overlooked and not considered for GHG emissions reduction options. This study aims to understand the impact and order of magnitude of scope 1, scope 2 and scope 3 GHG emissions of innovative value chains on industry. Therefore, it assesses the full value chain GHG emissions of innovative technologies in industry. Addressing different scopes of emissions can reveal new opportunities to reduce GHG emissions and avoid potential adverse indirect effects and problem shifting (Uslu, A., Oliveria, C., Brouwer-Milovanovic, M. & Moncada, J., 2022).
- › The innovations covered in this study are direct electrification of steam crackers, ethylene production using lignocellulosic feedstocks, use of renewable ammonia (via renewable hydrogen) for producing fertilisers and methanol production from waste, specifically refuse derived fuels (RDF).
- › The results confirm the relevance of analyzing GHG emissions performances of innovations in industry from a complete value chain perspective. While some of the innovations may result in significant GHG emissions reductions in scope 1, their full value chain effects could be relatively limited when considering other scopes of emissions. Therefore, policy incentives should also include mechanisms that target scope 3 GHG emission reductions, in addition to the innovations in industry. More specific case study results are as follows:
- › There is significant potential to reduce scope 1 and scope 2 GHG emissions through direct electrification of crackers by supplying electricity from renewable sources. Consequently, the availability of renewable electricity (and infrastructure) is a key variable in reducing GHG emissions in electric cracking. In addition, hydrogen production from the remaining fuel gas and Carbon Capture and Storage (CCS) contributes to the overall GHG emissions reduction. However, the embedded fossil carbon in naphtha and its release at the end-of-life continue to be the largest source of GHG emissions over the entire value chain. These GHG emissions largely steer the overall performance and can exceed the scope 1 and scope 2 GHG emissions savings. Therefore, further action is needed to substitute fossil naphtha with renewable and/or circular options.

› EXECUTIVE SUMMARY

- › The ethylene production from lignocellulosic feedstocks reflects the use of sustainable biomass resources. In this case, not only scope 1 GHG emissions, but also scope 2 and 3 emissions reduce significantly. In addition, the overall value chain GHG emissions become negative as by-products from the production process can substitute fossil-based combustion and provide credits to the GHG emissions accounting.
- › The use of renewable H₂ in fertilisers value chains illustrates that direct CO₂ release (scope 1) during steam methane reformer can be entirely avoided. In addition, the supply location of renewable hydrogen-based ammonia is less relevant as ammonia transport-related GHG emissions are low in comparison to other emissions in the value chain. However, the N₂O-related scope 1 GHG emissions during nitric acid production remain unchanged compared to the conventional production route. Also, direct and indirect (N₂O) emissions from fertilisers applications (use-phase in agriculture) are the major source of GHG emissions over the entire value chain. Thus, further actions and innovations are required to reduce N₂O related scope 1 and scope 3 GHG emissions.
- › Methanol production from RDF results in increased scope 1 GHG emissions, when compared with the natural gas-to-methanol production. This is due to the fossil content of waste and the fossil carbon release during the gasification process. The full value chain GHG emissions, including end-of-life combustion, result in minimal GHG emission savings compared to the fossil reference. The emission savings are attributed to the RDF biogenic share and zero GHG emissions allocated (upstream from collection) to recycled RDF. Production of chemicals from methanol and further circularity of the end-products can increase this innovation's full value chain GHG performance. In addition, increasing the biogenic carbon content of RDF mix and improving the gasification conversion efficiency can reduce these GHG emissions.

EXECUTIVE SUMMARY

MAIN MESSAGES

- It is vital to focus on full value chain GHG emissions (scope 2 and scope 3) and not only on the performance of scope 1 GHG emissions in industry innovations. Therefore, policy design should aim at reducing the overall value chain GHG emissions.
- Using renewable electricity should be prioritised for the direct electrification of steam crackers. Furthermore, substituting fossil naphtha with renewable and circular options should be incentivized.
- Reducing GHG emissions in fertilisers' value chains requires shifting to renewable ammonia use, and good agricultural practices that aim to reduce direct and indirect N₂O emissions.
- The RDF-to-methanol value chain results in limited GHG emissions savings when the methanol is assumed to be combusted. However, different options should be explored as they will improve the overall value chain GHG performance. A good example can be using methanol as a building block for the chemical industry (store of (biogenic) carbon) coupled with recycling options at the end-of-life.
- All the assessed innovations are relevant to reducing scope 1 GHG emissions in the Netherlands. However, substituting fossil feedstocks with renewable and sustainable resources and reducing scope 3 emissions remain one of the industry's main challenges.

› INTRODUCTION

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› INTRODUCTION

A FULL VALUE CHAIN ASSESSMENT OF INNOVATIONS IN INDUSTRY

- › The Dutch industry will go through a significant transformation over the coming years and the new innovative technologies and processes required to facilitate this will be vastly different from the current situation. According to the GHG Protocol (GHG protocol, 2022), for many companies, substantial emissions linked to their processes may occur outside the company's direct operation. However, current policy instruments targeted at industry in the Netherlands are aimed at measures that reduce their direct process emissions. The GHG Protocol refers to these process emissions as scope 1 emissions. Emissions associated with the supply of electricity, steam and heat to the production processes are referred to as scope 2 emissions and Scope 2 emissions are addressed under the energy sector-related decarbonisation incentives. All other emissions, upstream and downstream, are referred to as scope 3 emissions, and these are not always well covered by research to know what and how large these emissions are.
- › The Ministry of Economic Affairs (EZK) asked TNO to study the full value chain GHG emissions effects of innovations in industry, where the emissions can be broken down to different scopes, and also to determine where these emissions are likely to occur, whether that be in the Netherlands or abroad.
- › The main goal of this study is to support the Ministry in understanding the full value chain GHG effects of innovative technologies. The following research questions are addressed in this study:
 - › What are the full value chain GHG emissions of selected innovations, in comparison with the fossil reference value chains?
 - › What are the main steps contributing to these emissions?
 - › What are the scope 1, 2 and 3 emissions?
 - › Do the possible emission savings in scope 1 contribute significantly to the overall value chain emission savings?
 - › How large are the emissions, and the emission savings potential for the Netherlands?

› INTRODUCTION

SELECTION OF THE CASE STUDIES

Four different case studies were chosen together with the Ministry for the assessment. While two case studies relate to substituting fossil raw material use in industry with renewable options, one case study focuses on the use of refuse derived fuel (RDF), and the other one relates to change of heat and steam use from fossil energy sources to electricity. The selected case studies are as follows:

- › **Electrification of steam cracking:** In the Netherlands, there are six operating steam crackers with a total ethylene nameplate capacity of over 4000 kt/year. Excluding refineries, the chemical industry in the Netherlands was responsible for over 18 Mt GHG emissions (Olivera; CBS, 2021a, CBS, 2021b), and the estimated yearly furnace emissions were around 4 Mt CO₂ (Oliveira, C., Moncada, J., West, K. & Apeldoorn, T., 2021; Oliveira, C. & van Dril, T., 2021). This corresponds to around 26% of the total GHG emissions of the chemical industry. Electrification of steam crackers has been a topic of interest by a large number of companies within the petrochemical industry, both in and outside of the Netherlands, with the aim of reducing GHG emissions. Given that complex production sites such as steam crackers are highly integrated, changes to one part of the process might require modifications in other parts (Oliveira, C. & van Dril, T., 2021). In this case study, the full value chain GHG emissions effects of ethylene production from fossil naphtha is assessed, where the steam cracking energy demand is met fully by electricity. The end-of-life stage is also included in this assessment to provide a complete picture. This value chain is compared with the conventional naphtha cracking value chain.
- › **Ethylene production using biomass resources:** Ethylene is one of the most important intermediate products in the petrochemical sector, and an essential building block for several products, such as linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polyesters and resins. The six operating steam crackers in the Netherlands produced around 2,2 Mt/year ethylene in 2019, making the country responsible for around 14% of all European ethylene production. Production of ethylene using biomass resources is one of the ways to substitute for conventional fossil fuel-derived ethylene and to significantly reduce life cycle GHG emissions. Bio-ethylene production via sugarcane ethanol was assessed in 2021 (Uslu et al., 2021). In this case study, we focus on bio-ethylene production using wood chips, presenting the full value chain GHG emissions impacts.

› INTRODUCTION

SELECTION OF THE CASE STUDIES

- › **Low carbon fertiliser production, using renewable hydrogen (H₂):** In the Netherlands, the two large fertiliser producers, Yara Sluiskil and OCI BV, emitted more than 5 Mt GHG emissions in 2017 (Bataal &Wetzels, 2019). These companies have been researching the potential for renewable H₂ use to reduce their carbon footprint. Replacing natural gas-based ammonia with renewable ammonia will result in different GHG emissions savings depending on many factors, such as whether the renewable ammonia and/or renewable H₂ will be produced in the Netherlands or imported from elsewhere, and what the CO₂ source for urea production will be. In this case study, the full value chain GHG emissions effects of renewable ammonia-based fertiliser production and use are assessed and compared with a generic conventional fertilisers production and use.
- › **Waste-to-methanol production:** Production of methanol via high-temperature gasification of municipal solid waste (MSW) and non-recyclable plastics is an alternative, circular substitution for producing methanol from natural gas. There is a growing interest in sustainable methanol production as it is a flexible product, which can be used as the chemical building block for the production of plastics, paints, cosmetics and as transport fuel. For instance, GIDARA Energy has announced their plans for an advanced methanol facility at the Port of Rotterdam, where approximately 90 kt of methanol will be produced using non-recyclable waste (PoR, 2022). In this case study, the full value chain GHG emissions of a generic refuse derived fuel (RDF)-to-methanol value chain is assessed and compared with the conventional methanol production using natural gas.
- › The detailed background calculations will be published in a user friendly TOOL, where the users can follow the detailed calculations and also change some of the input parameters and conduct sensitivity analysis.

INTRODUCTION

APPROACH

- › A good understanding of the GHG emissions of the innovative options, including circular and biobased options for Dutch industry, requires a consistent and transparent accounting approach.
- › The approach used in this study is based on the Life Cycle Assessment principles presented in the ISO guidelines (ISO, 2006). Figure 1 shows the system boundary, which includes feedstock production and supply to intermediate conversion, supply of intermediates to the main production and production itself, and end-of-life, including transport. The system boundary can be adjusted to any type of value chain, and steps that are not relevant to a particular case can be omitted. This figure also introduces how the GHG emissions occurring in different steps are categorized as scope 1, 2 and 3, from the perspective of the main production activity.
- › The functional unit acts as the quantification standard and was chosen in accordance with the goal and the scope of the case studies. To the full extent possible, it was kept identical for all scenarios analysed, ensuring comparability between the scenarios.
- › Product perspective was chosen in this study as it gives the equal basis for comparison between scenarios, as well as between different value chains for the same target product (Uslu, A., Oliveria, C., Brouwer-Milovanovic, M. & Moncada, J., 2022).

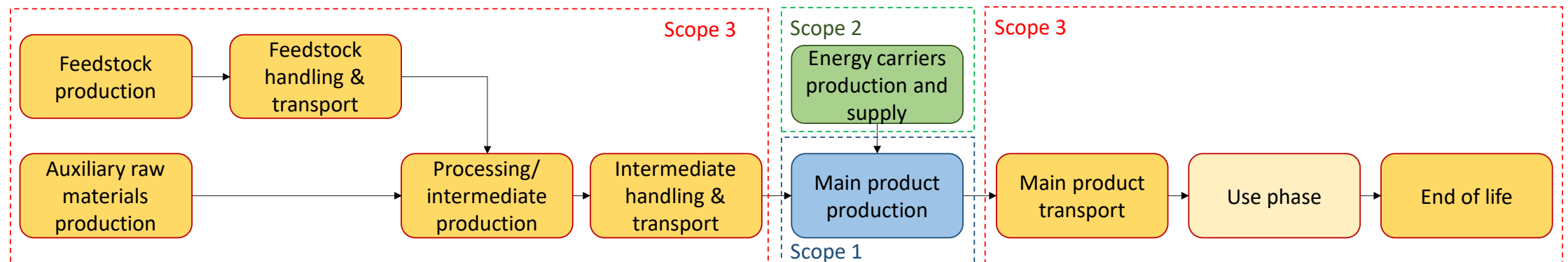


Figure 1. Generic flow diagram showing the system boundaries and the classification of different steps to scope 1, 2 or 3.

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CASE STUDY RESULTS

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ELECTRIC CRACKING CASE STUDY

INTRODUCTION

BACKGROUND AND OBJECTIVES

- Steam cracking is the process within the chemical industry that breaks long-chain hydrocarbons into short-chain to produce high value chemicals. The thermal energy required for the steam cracking process is supplied by fuel gas, which is one of the by-products from the cracking reactions (Figure 2). This fuel gas is combusted in furnaces to produce steam, resulting in large amounts of direct CO₂ emissions. The estimated furnace emissions of steam crackers in the Netherlands were around 4 Mt CO₂/yr in 2019 (Oliveira, C., Moncada, J., West, K. & Apeldoorn, T., 2021).
- Direct electrification of steam cracking is currently proposed by a number of chemical companies, including BASF, Dow Chemicals, Shell, BP, Borealis and LyondellBasell (Shell, 2022; SABIC, 2022; Hydrocarbon Processing, 2021; Brightlands, 2020). This option can help mitigate scope 1 emissions, however, the reduction achieved will depend on the repurposing of fuel gas that becomes available. The total GHG emissions reduction potential of this innovation will also depend on the source/origin of electricity because of scope 2 emissions. There is limited research on the GHG emissions effects of electric cracking. This case study analyses the full value chain GHG emissions effects of electrification of steam cracking and the use of fuel gas for other purposes.

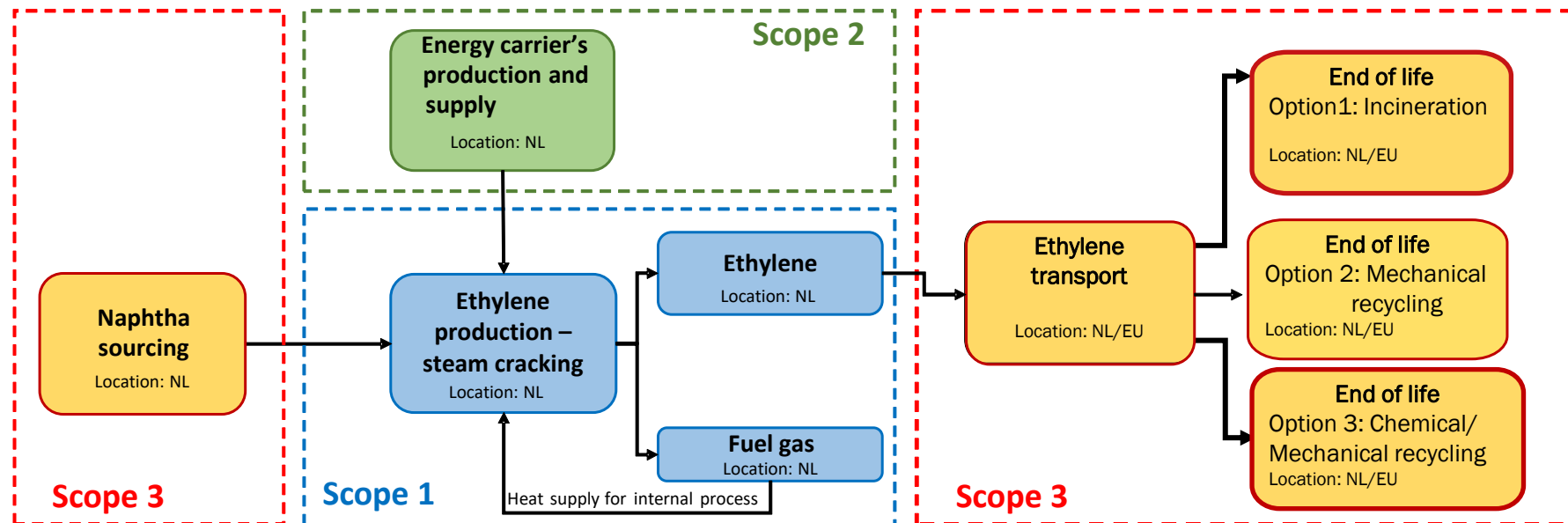


Figure 2. Generic conventional steam cracking flow diagram showing the system boundaries and the classification of different steps to scope 1, 2 or 3.

› ELECTRIC STEAM CRACKING SUPPLY CHAIN DIAGRAM & SYSTEM BOUNDARIES

- › While the focus is on electrification of steam cracking, this analysis covers the full value chain, including different end uses. Figure 3 illustrates the flow diagram of a generic electric cracking system, where different steps are grouped as either scope 1, 2 and 3, from the perspective of the cracker's facility.
- › In this case study, heat demand of furnaces and also the compressors are assumed to be fully met by electricity. The residual fuel gas is considered to be used for blue hydrogen production via Autothermal reforming (ATR), followed by carbon capture and storage (CCS). This hydrogen can be sold to third parties and used as feedstock.
- › 1 tonne ethylene is used as the functional unit and the total GHG emissions are allocated to this product. The functional unit includes production, use and end-of-life. Steam cracking produces multiple products, referred to as high-value chemicals. The mass balance approach is used to allocate the emissions to ethylene. All of the assumptions used in this study can be found in Annex I.

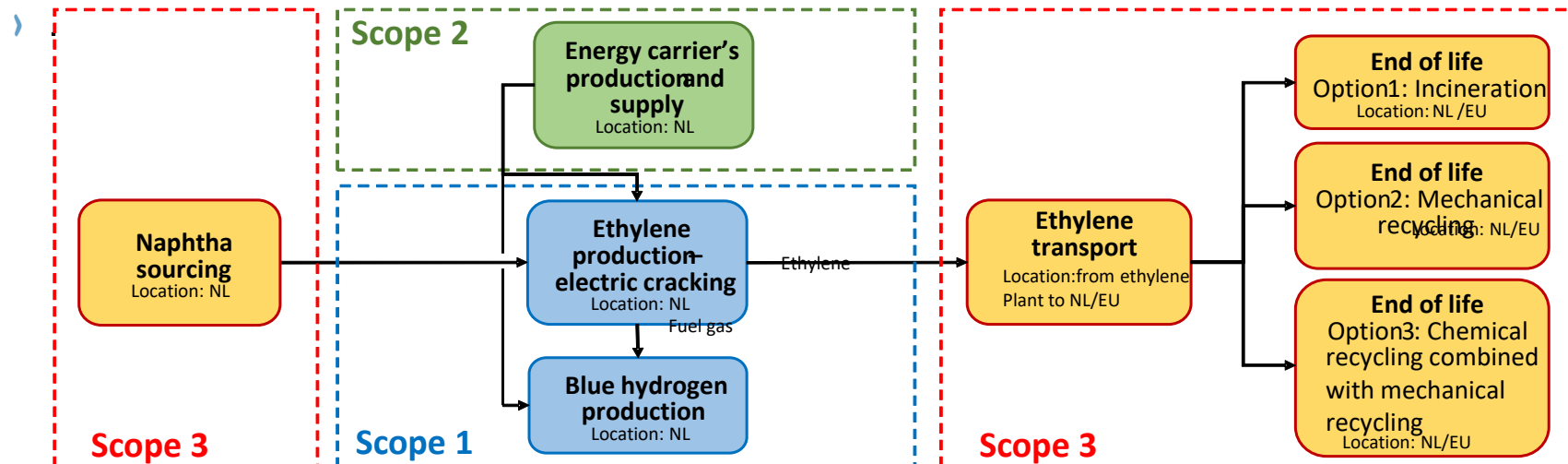


Figure 3. Electric steam cracking value chain diagram showing the system boundaries and the classification of different steps to scopes 1, 2 and 3.

RESULTS

GHG EMISSIONS OF ELECTRIC CRACKING IN COMPARISON TO CONVENTIONAL REFERENCE (CRADLE-TO-GATE)

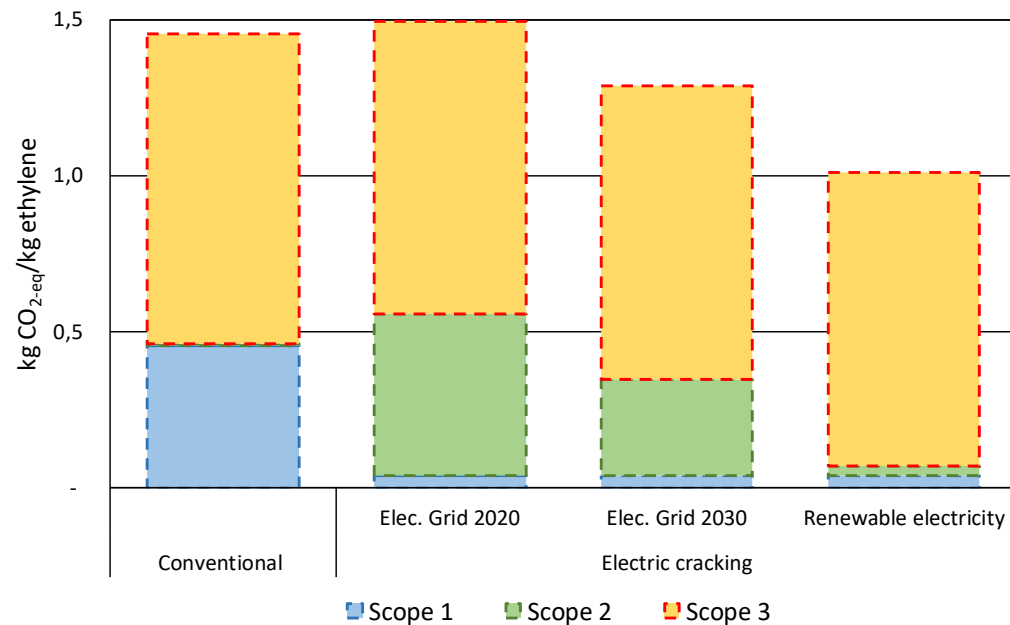


Figure 4. GHG emissions grouped as scope 1, 2 or 3 for both the conventional steam cracking and electric cracking value chains.

* Elec. Grid 2020: electricity demand is provided by the grid, the emission factor for the electricity is 0,292 kgCO_{2eq}/kWh (PBL, 2022).

* Elec. Grid 2030: electricity demand is from the grid. The emission factor is 0,168 kgCO_{2eq}/kWh (PBL, 2020).

* Renewable electricity: electricity is sourced by wind turbines, with the zero emission factor (JRC, 2020).

- Figure 4 illustrates the cradle-to-gate GHG emissions. This covers the steps related to supply of fossil naphtha and the cracking of naphtha to high value chemicals. For the electric cracking value chain, the conversion of fuel gas to H₂ is also included in the cradle-to-gate GHG emissions.
- Scope 1 emissions refer to direct emissions generated during either the cracking process in conventional value chain or during the hydrogen production in the electric cracking value chain.
- In the conventional value chain, scope 2 emissions include electricity consumption for small equipment like pumps and small compressors. For the electric cracking value chain, scope 2 emissions include the electricity input for small equipment, electric furnaces, electric compressors and the steam demand for the blue H₂ production unit.
- Scope 3 emissions relate to the naphtha supply (based on an average value for supply to Europe) and is the same for all options presented in this figure.

› RESULTS

GHG EMISSIONS OF ELECTRIC CRACKING IN COMPARISON TO CONVENTIONAL REFERENCE (CRADLE-TO-GATE)

- › It is important to note that the estimated heat distribution in the electric cracking value chain resulted in higher thermal efficiency, when compared to the conventional cracking system (based on fuel gas). The total energy input in the electric cracking value chain is 23% lower than the input for the conventional process. Detailed information regarding the heat distribution in both conventional and electric cracking systems is present in Annex-1.
- › In all options, the largest emissions relate to the supply of fossil naphtha to the Netherlands, which is highlighted in yellow in Figure 4. The emission factor used for the naphtha supply is 0.32 kgCO_{2eq}/kg naphtha. This value is estimated based on calculations using the total emission factor for the ethylene production at the gate (1.45 kgCO_{2eq}/kg ethylene, ECOINVENT 3 database) and the energy balance for a typical steam cracker system (A. Boulamanti and J.A. Moya , 2017).
- › Using the latest Dutch electricity mix data (from 2019), direct electrification of steam cracking process and the compressors result in slightly lower GHG emissions than the fossil reference (around 3% lower). This relates mainly to the significantly large amount of electricity demand (50 times higher than the electricity input in the conventional reference) and the electricity grid emission factor.
- › Figure 3 also shows the importance of renewable electricity use. When electricity demand is met fully by renewable sources, Scop1 and 2 emissions of crackers can be reduced by 85% (alone scope 1 emissions can be reduced by more than 90%) and the total emissions at the gate by ~30%.
- › Thus, this study finds that there is significant potential for overall emission reductions through the direct electrification of crackers, with the condition that this electricity is supplied from renewable sources.

RESULTS

FULL VALUE CHAIN GHG EMISSIONS

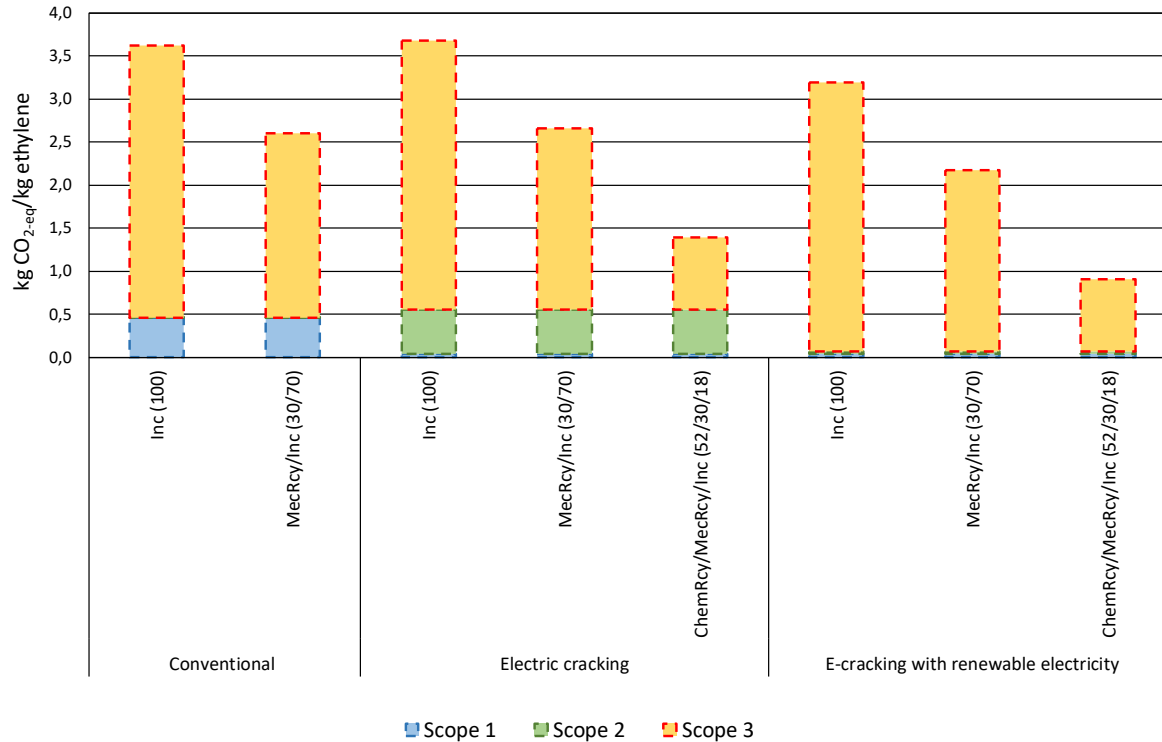


Figure 5. GHG emissions in different steps to scope 1, 2 or 3, including different end-of-life options for both the conventional steam cracking and electric cracking value chains.

- *Inc (100): All ethylene-based products are fully incinerated
- *MecRcy/Inc: 30% is mechanically recycled. The remaining 70% is incinerated
- *ChemRcy/MecRcy/Inc: 52% chemically, 30% mechanically recycled and the remaining incinerated

- › Figure 5 shows the relative contribution of direct electrification of cracking to the full value chain GHG emissions, where the end-of-life is also included.
- › The overall emission reductions potential of direct electrification appears less prominent, even for the cases with renewable electricity use. This relates to the significant amount of embedded fossil carbon in the products and its release at the end of life. Around 44-60% of the total emissions relate to this stage for the conventional value chain
- › Thus, the choice of end-of-life plays a crucial role in the full value chain emissions. For instance, the emission reductions can reach to 75% for the renewable electric cracking case, with the end-of-life, where a significant amount of the products are chemically and mechanically recycled, compared to the conventional reference with the incineration EoL.
- › The results underline the need to substitute the feedstock use with sustainable and renewable feedstocks if further emission reduction goals are to be achieved.
- › The breakdown of each step in the value chain is presented in Table 1.

RESULTS

FULL VALUE CHAIN GHG EMISSIONS

Table 1. GHG emissions in different steps to scope 1, 2 or 3, including different end-of-life options for both the conventional steam cracking and electric cracking value chains.

		Conventional		Electric cracking			Electric cracking (renewable electricity)		
		Inc (100)	MecRcy (30/70)	Inc (100)	MecRcy/Inc (30/70)	ChemRcy/MecRcy/Inc (52/30/18)	Inc (100)	MecRcy/Inc (30/70)	ChemRcy/MecRcy/Inc (52/30/18)
Scope 3	Feedstock supply	0,99	0,99	0,94	0,94	0,94	0,94	0,94	0,94
Scope 2	Ethylene production	0,01	0,01	0,47	0,47	0,47	0,00	0,00	0,00
	Blue hydrogen production	0,00	0,00	0,05	0,05	0,05	0,03	0,03	0,03
Scope 1	Ethylene production	0,46	0,46	0,00	0,00	0,00	0,00	0,00	0,00
	Blue hydrogen Production	0,00	0,00	0,04	0,04	0,04	0,04	0,04	0,04
Scope 3	CO2 transport	0,00	0,00	0,02	0,02	0,02	0,02	0,02	0,02
	Ethylene transport	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
	End of life	2,15	1,13	2,15	1,13	-0,14	2,15	1,13	-0,14
	Total	3,63	2,60	3,68	2,66	1,39	3,20	2,18	0,90

* Units kg CO_{2-eq}/kg ethylene

*Inc (100): All ethylene-based products are fully incinerated

*MecRcy/Inc: 30% is mechanically recycled. The remaining 70% is incinerated

*ChemRcy/MecRcy/Inc: 52% chemically, 30% mechanically recycled and the remaining incinerated

SENSITIVITY CASE

DIFFERENT ELECTRIFICATION LEVEL

Assumptions

- › Full electrification of the steam cracking furnaces and compressors is expected to occur in steps due to the insufficient availability of renewable electricity and related infrastructure, and to the maturity of the electrification technology. Therefore, this sensitivity focuses on a hybrid systems in order to understand the transition of a conventional steam cracking facility to an electric system.
- › This case considers that only the gas-fired furnaces are replaced by electric furnaces and the compressors are driven with steam turbines, as is the case in the conventional system. This steam demand is supplied by boilers using the residual fuel gas from the electric furnaces.

Results

- › The total energy input need of this sensitivity case appears to be 35% less than the conventional steam cracking system. This is because steam super-heating is no longer needed in this case. However, the steam production via fuel gas boiler results in significant scope 1 emissions (0.15 kg CO_{2eq}/kg ethylene) (See figure 6).
- › The results show that the cradle-to-gate emissions are 5% higher than the electric cracking baseline value chain and 8% higher than the conventional cracking reference.

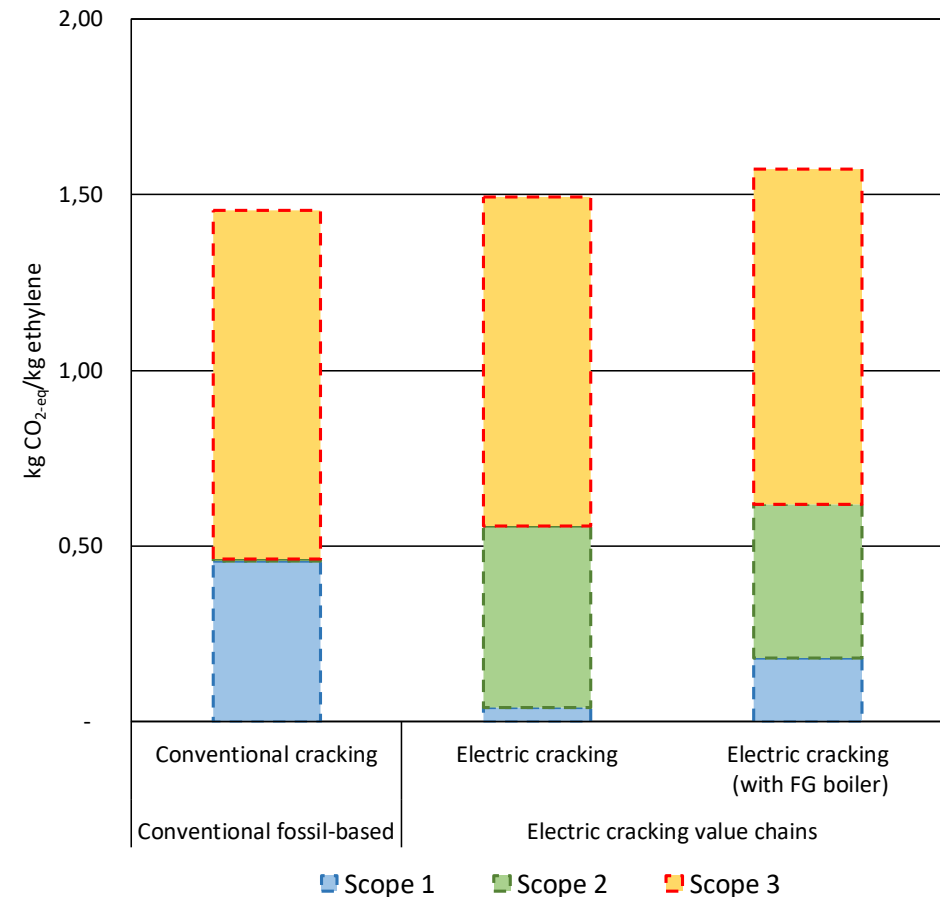


Figure 6. Cradle to gate GHG emissions in different steps to scope 1, 2 or 3 for the conventional reference, for the baseline electric cracking value chain and the sensitivity case

* Electricity demand is provided by the grid, the emission factor for the electricity is 0,292 kgCO_{2eq}/kWh (PBL, 2022).

SENSITIVITY CASE

FUEL GAS COMBUSTION ELSEWHERE

Assumptions

- › Full electrification of the steam cracking furnaces and compressors is considered and the residual fuel gas is exported to be used outside the fence of the steam cracking site.
- › The fuel gas is assumed to be combusted, and both LHV and emission factors are estimated based on the typical fuel gas composition shared by the interviewed companies.

Results

- › No scope 1 emissions are present in this sensitivity case because all fuel gas is exported and used elsewhere. However, scope 3 emissions are 25% higher than the conventional cracking and 32% higher than the baseline electric cracking case (see Figure 7).
- › The results show that the GHG emissions (cradle-to-gate + FG combustion outside the fence) are 11% higher than the electric cracking baseline value chain and 14% higher than the conventional cracking reference.

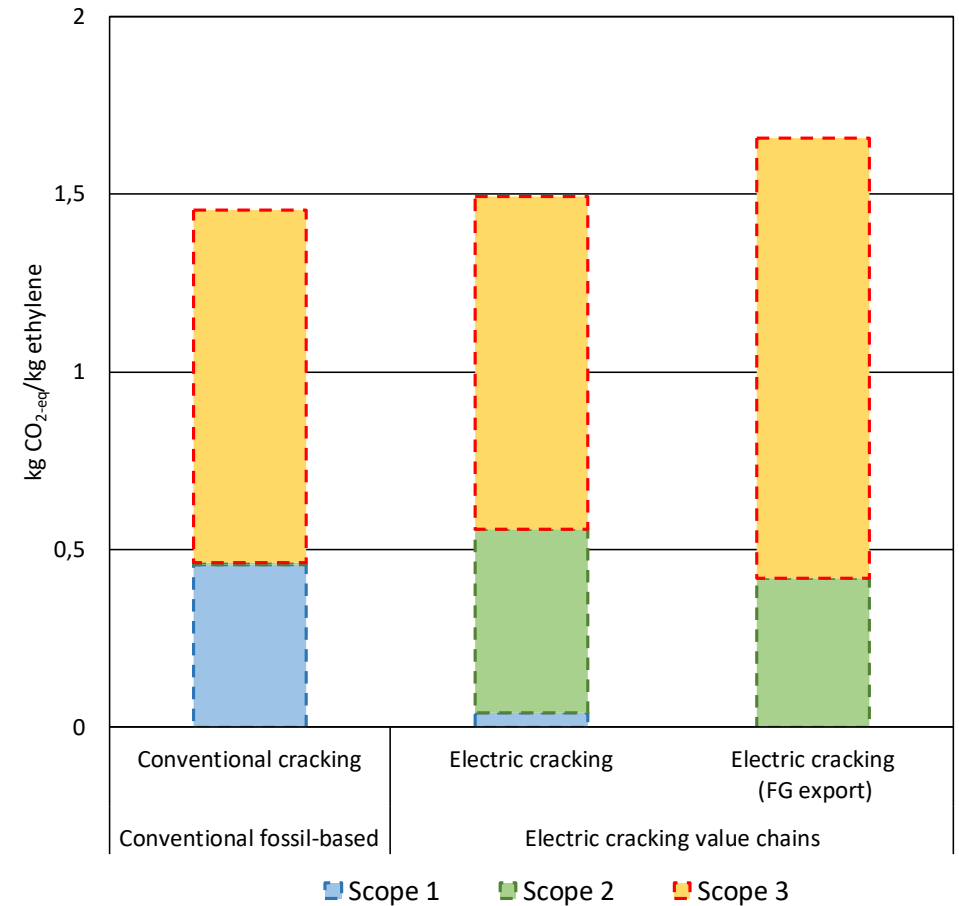


Figure 7. GHG emissions in different steps to scope 1, 2 or 3 for the conventional reference, for the baseline electric cracking value chain and the sensitivity case

* Electricity demand is provided by the grid, the emission factor for the electricity is 0,292 kgCO_{2,eq}/kWh (PBL, 2022).

› CONCLUSIONS AND LIMITATIONS

- › The results show that full electrification of crackers and compressors improve the energy efficiency of the system. The calculated total energy input in the electric cracking value chain is 26% lower than the input for the conventional process.
- › Ethylene production via direct electrification has a significant potential to reduce scope 1 emissions of crackers that occur in the Netherlands, by 90%. However, this emission savings can be compensated or even overshoot by the electricity supply related scope 2 emissions. Thus, the availability of sufficient renewable electricity (and infrastructure) is key to releasing the full emission reduction potential. With full renewable electricity use, scope 1 and 2 total emissions can be reduced by 85%.
- › The fossil naphtha supply and the end-of-life of products that contain embedded fossil carbon, continue to be the largest sources of GHG emissions. In fact, when these steps are included the full value chain emissions are reduced by only ~30%, even fully renewable electricity supply is considered.
- › Repurposing the residual fuel gas when electrification takes place is determinant for the overall GHG emissions of this value chain. In case the residual stream is combusted outside the fence of the steam crackers, the scope 1 emissions are extinguished, however, scope 3 emissions are 25% higher than the conventional cracking system.

Limitations

- › The material yields for the fossil reference is based on the average steam cracking process in the EU, as indicated by the JRC report from Boulamanti and Moya (2017). Although, the steam cracking technology is quite similar throughout Europe, the mass balance considered might not reflect exactly the Dutch steam cracking sites.
- › The well-to-gate ethylene production GHG emissions are based on the Ecoinvent database for the conventional reference case. This data is different than the EU ETS benchmark for the HVC production from steam cracking. The ETS benchmark refers to the 10% least emitting plants in Europe and focuses only on the direct CO₂ emission, whereas Ecoinvent includes all of the GHG emissions, including the used chemicals and materials (EC,2021). Since the same data is used both for the conventional fossil reference and the electric cracking case the data source becomes less of an issue.

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ETHYLENE PRODUCTION FROM LIGNOCELLULOSIC BIOMASS

INTRODUCTION

BACKGROUND AND OBJECTIVE

- › A significant share of the GHG emissions of fossil fuel-based ethylene relates to the upstream emissions associated with fossil naphtha supply, and downstream emissions related mostly to the release of embedded fossil carbon emissions at the end-of-life (EoL) stage.
- › Bio-based value chains absorb carbon from the atmosphere. This carbon remains in the material for a period of time, and is then released to the atmosphere (or not), depending on the EoL treatment. This enables carbon neutrality and therefore reduces CO₂ emissions compared to fossil-based sources. Replacing fossil naphtha feedstock with biomass resources can significantly reduce these scope 3 emissions. To illustrate, ethylene production using sugarcane ethanol (Uslu et al., 202) has been shown to reduce GHG emissions between 85-89% compared to the conventional fossil reference case (depending on location and EoL). In this case study, lignocellulosic residues are chosen, as the use of residues from the agricultural and forest industries does not lead to any substantial direct or indirect land use changes.

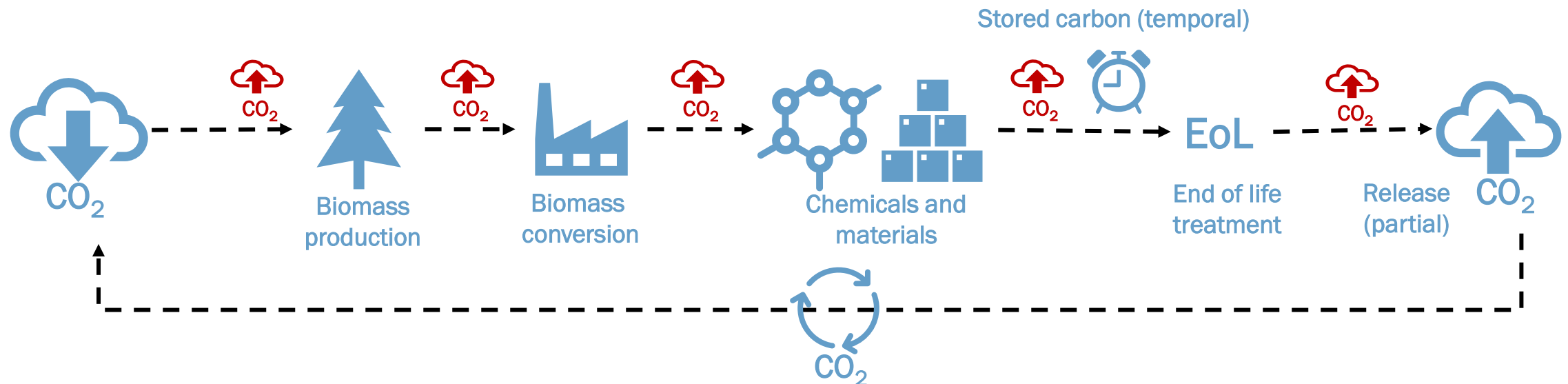


Figure 8. Schematic presentation of biogenic CO₂ cycle

THE SUPPLY CHAIN OVERVIEW

SUPPLY CHAIN DIAGRAM & MAIN ASSUMPTIONS

- › Forest residues from the Baltic States (BS) is considered the main feedstock as the Netherlands (NL) has a limited sustainable lignocellulosic biomass potential (Panoutsou et al., 2016; Bioenergy Europe, 2018). The BS provide a high potential for forest residues and there is an established supply chain between the BS and the NL for wood chips (pellets) (Bioenergy Europe, 2018). The system boundaries cover the forest residue collection-to-ethylene production and the end-of-life. Figure 21 shows the system boundaries and the location of the supply chain stages.
- › Functional unit set to 1 kg of ethylene. The functional unit includes production and the-end-of-life. This enables a comparison with alternative ethylene production routes.
- › The lignin is used in a Combined Heat and Power (CHP) system to provide heat and electricity for the ethanol conversion process. Additional heat and electricity required in other steps of the value chain, such as the ethanol to ethylene conversion system, is provided from the grid.
- › Incineration with energy recovery (option 1) and mechanical recycling (option 2) are explored as EoL alternatives. Carbon release is calculated as being zero due to the biogenic nature of the molecule. Option 2 reflects the current implementation in the Netherlands, whereby 30% is mechanically recycled and the remaining 70% is incinerated.

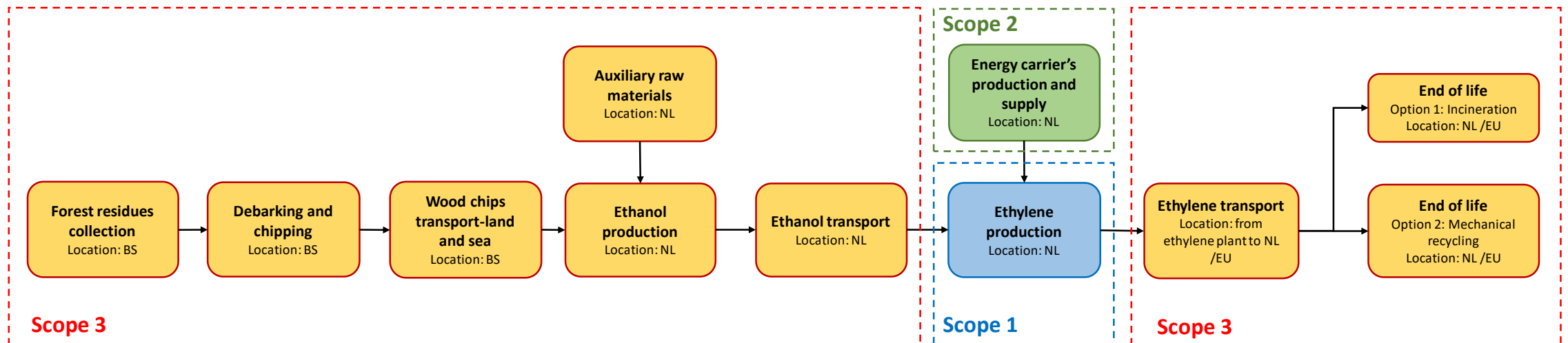


Figure 9. Schematic representation of bio-based ethylene value chain

RESULTS

COMPARISON OF ALTERNATE CASES WITH FOSSIL-BASED REFERENCE (CRADLE-TO-GRAVE)

- Compared to the fossil alternative, producing biobased ethylene from forest residues results in lower GHG emissions over the entire value chain.
- All biobased alternatives, independently of the EoL treatment and location, result in negative CO₂ emissions. This is mainly related to forest residues' high lignin content (burnt in a CHP) that covers the heat and electricity demand of the ethanol conversion process. A GHG emission credit is given for the additional lignin-based electricity returned to the grid, which considerably exceeds the conversion to ethanol electricity demand.
- For the biobased alternatives there is no significant difference between EoL treatments and location in relation to the total supply chain GHG emissions.

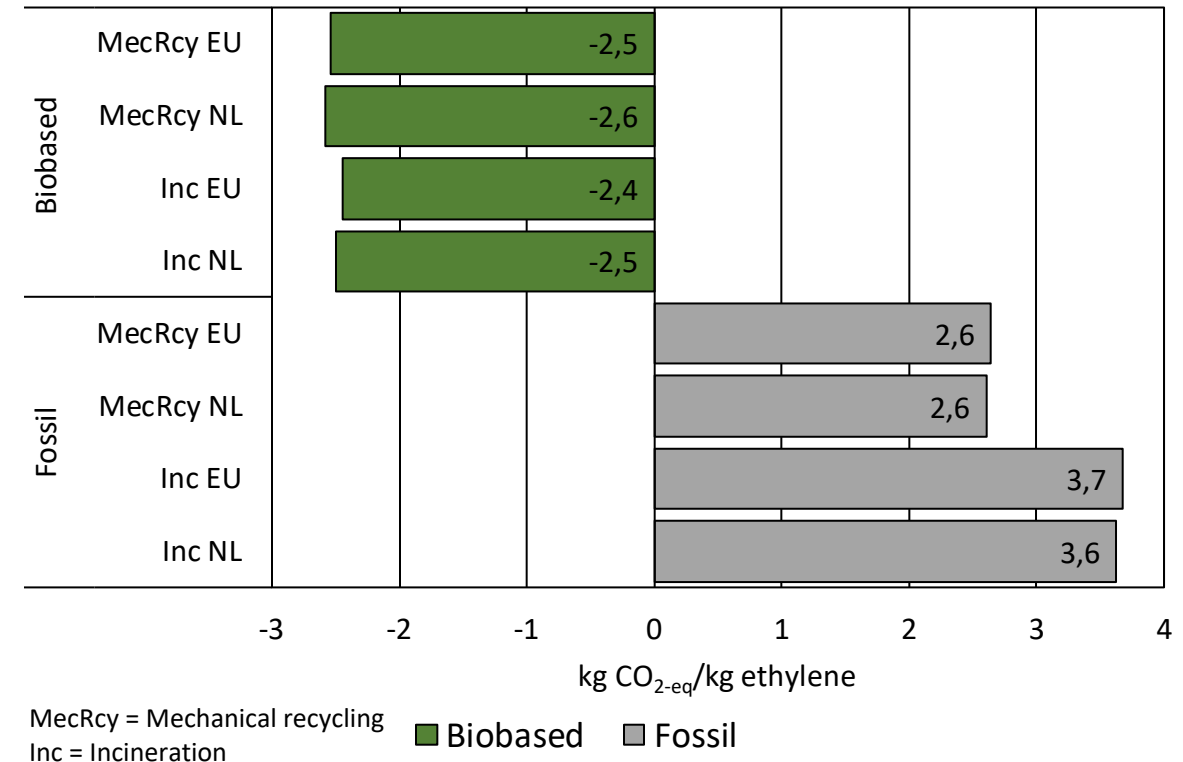


Figure 10. Ranking of bio ethylene production value chains in comparison to fossil ethylene (cradle-to-grave).

RESULTS

GHG EMISSIONS IN THE NETHERLANDS VERSUS ABROAD

- There is a considerable difference in GHG emissions intensity between the different locations. For abroad (mainly the Baltics States up to pellets delivery for ethanol conversion), emissions are positive, while in the Netherlands (from biomass conversion to ethanol and ethylene up to ethylene transport for EoL treatment) are negative.
- Since ethanol production was assumed to occur in the Netherlands, most of the GHG emissions savings are accounted for in this country. These savings are mainly related to additional electricity provided to the grid at the biomass-to-ethanol conversion stage.
- However, if ethanol production were carried out in the Baltic States and later transported to the Netherlands for ethylene conversion, GHG emissions savings would be accounted for in the Baltic States. In addition, the carbon intensity of the electricity mix in the Baltic states is higher compared to the Netherlands. Thus, credits for additional electricity provided to the grid would result in higher GHG emission savings.
- In terms of EoL, there is no significant difference in the GHG emissions intensity between the EoL location, given that the average carbon intensity of the European electricity mix and heat delivery from natural gas is similar to the one of the Netherlands. Therefore, the EoL GHG emission credits for heat and electricity substitution are similar for both considered locations.

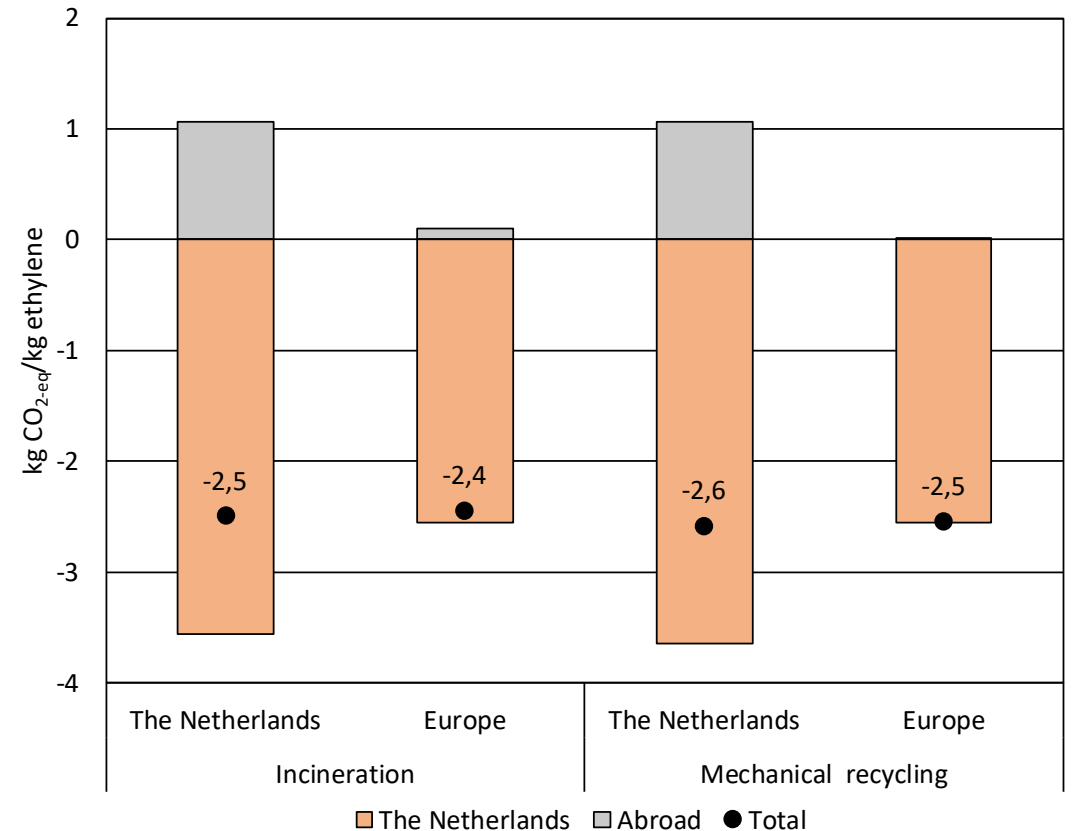


Figure 11 Ranking of fertiliser value chains related to the location of GHG emissions between the Netherlands and abroad

RESULTS

GHG EMISSIONS SCOPES AND SUPPLY CHAIN STAGES

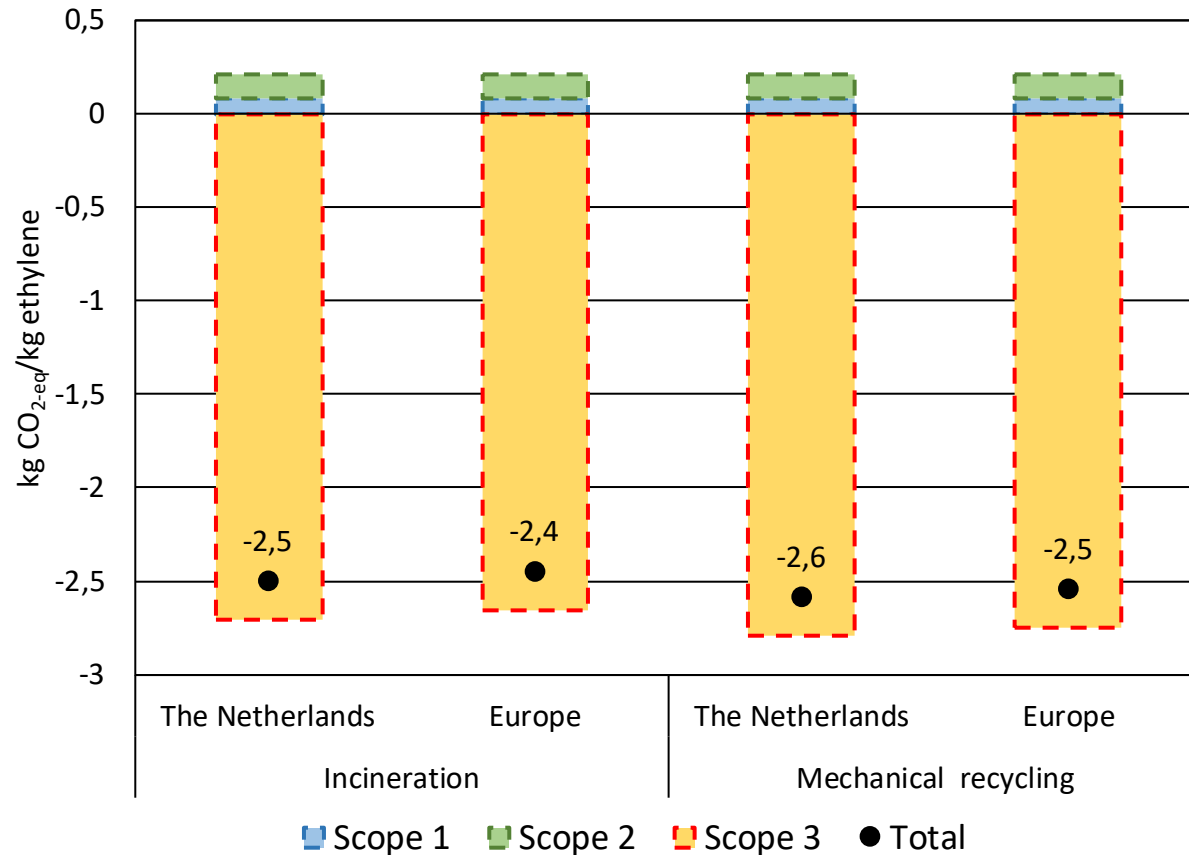


Figure 12. Full value chain GHG emissions broken down to different scopes

Table 2. GHG emissions of bioethylene production and use broken down to different scopes

	Incineration		Mechanical Recycling		
	The Netherlands	Europe	The Netherlands	Europe	
Scope 3	Feedstock collection	0,34	0,34	0,34	0,34
	Debarking and chipping	0,30	0,30	0,30	0,30
	Feedstock transport land	0,26	0,26	0,26	0,26
	Feedstock transport sea	0,16	0,16	0,16	0,16
	Ethanol production	-2,81	-2,81	-2,81	-2,81
	Ethanol transport	0,01	0,01	0,01	0,01
Scope 2	Ethylene production (heat and electricity)	0,13	0,13	0,13	0,13
Scope 1	Ethylene production	0,08	0,08	0,08	0,08
Scope 3	Ethylene transport	0,02	0,04	0,02	0,04
	End of life	-0,98	-0,96	-1,07	-1,05
Total		-2,5	-2,4	-2,6	-2,5

* Units kg CO_{2-eq}/kg ethylene

› RESULTS

GHG EMISSIONS SCOPES AND SUPPLY CHAIN STAGES

- › Scope 3 emissions contribute to the largest share of GHG emissions in the supply chain. However, total scope 3 GHG emissions are negative because of the additional electricity (credit) provided to the grid at the biomass-to-ethanol conversion stage in the Netherlands. Electricity-related credits depend on the electricity mix's carbon intensity, which is location and temporal specific.
- › The overall transport of forest residues to the palletisation plant, and later the pellets transport to the conversion and ethanol site contribute the most to overall supply chain emissions of the scope 3 GHG emissions.
- › Scope 1 and 2 GHG emissions have a low impact compared to scope 3 and other steps in the supply chain. The conversion of ethanol to ethylene requires lower energy use and fewer inputs than other processes.
- › There is not a significant difference between EoL treatment and location in terms of CO₂ emissions. However, mechanical recycling offers the alternative of processing plastic waste into secondary raw materials or products, while with incineration, only the energy is recovered.

› CONCLUSIONS AND LIMITATIONS

- › Ethylene production from lignocellulosic biomass offers a promising alternative to reduce GHG emissions compared to conventional fossil-based ethylene. In addition, it provides an opportunity to reduce the dependency on fossil-based feedstock in chemicals and materials supply chains.
- › The largest GHG emissions savings are attributed to the additional lignin burnt in the CHP at the ethanol conversion stage leading to credits for electricity production. However, the continually increasing share of renewable electricity in the European electricity mix can considerably reduce the carbon intensity and, therefore, the CO₂ credits for this supply chain. Nevertheless, even without the credits, biobased ethylene outperforms the fossil-based reference in terms of CO₂ emissions and provides surplus renewable electricity.
 - The use of lignin for heat and electricity supply has an important role in this supply chain. Thus, using different biomass types with lower lignin content can lead to lower CO₂ emissions savings. Forest residues have a high lignin content.
 - Lignin is valorised as an energy source in this study, but it can also be used for other purposes. Such other purposes are not included in this study.
- › There is a relatively small difference between EoL treatment and location in terms of GHG emissions. However, mechanical recycling offers an alternative to store carbon for a longer time in secondary raw materials or products, which is increasingly relevant under current GHG emissions trends.
- › Ethylene production from biomass may require significant amounts of feedstocks. Sufficient availability and possible competition for these biomass resources are not covered in this study as such an assessment is beyond the scope of this study.

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FERTILISERS FROM RENEWABLE AMMONIA

INTRODUCTION

BACKGROUND AND OBJECTIVES

- Ammonia is one of the world's most highly produced inorganic chemicals. Around 70% of ammonia is used to make fertilisers, with the remainder used for a wide range of industrial applications, such as plastics, explosives and synthetic fibres (IEA, 2021). Hydrogen is required for ammonia production and is traditionally derived from natural gas using steam methane reforming (SMR). The SMR process emits significant amounts of CO₂ in a pure form and during combustion.
- Renewable hydrogen is considered as one of the fertiliser industry's most important long-term decarbonisation options. It can replace hydrogen-derived natural gas use and significantly reduce GHG emissions. Thus, alternative supply chains for ammonia production should consider renewable hydrogen as an input for the production process. This study analyses the full value chain GHG emission impacts of renewable ammonia use to produce fertilisers. It focuses on both cradle-to-gate and cradle-to-grave emissions.

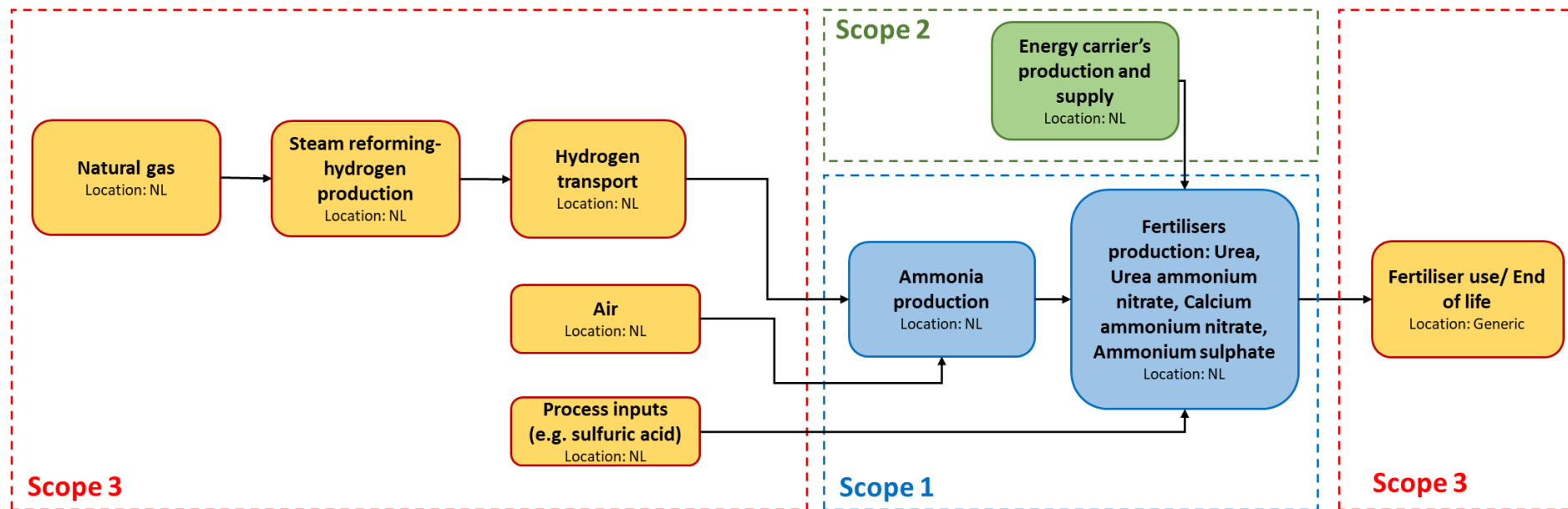


Figure 13. Generic flow diagram of fertilisers value chain

THE SUPPLY CHAIN OVERVIEW: ALTERNATIVE CASES

SUPPLY CHAIN DIAGRAM & MAIN ASSUMPTIONS

- › Two distinct supply options for renewable H₂ are considered.
- › **Option 1** assumes local production and supply of H₂ to the fertiliser industry. This option assumes that H₂ is produced from renewable electricity from North Sea offshore wind. This H₂ is used to produce ammonia and, subsequently, fertilisers in the Netherlands. In option 1, an air separation unit (ASU) would be required to supply nitrogen (N₂) to ammonia, whereas in the conventional reference, air is directly injected to the steam reformers where a mixture of H₂/N₂ is fed in the Haber-Bosh process reactor.
- › Figure 9 introduces the different steps within the value chain. It also groups the value chain-related GHG emissions as scope 1, 2 or 3.

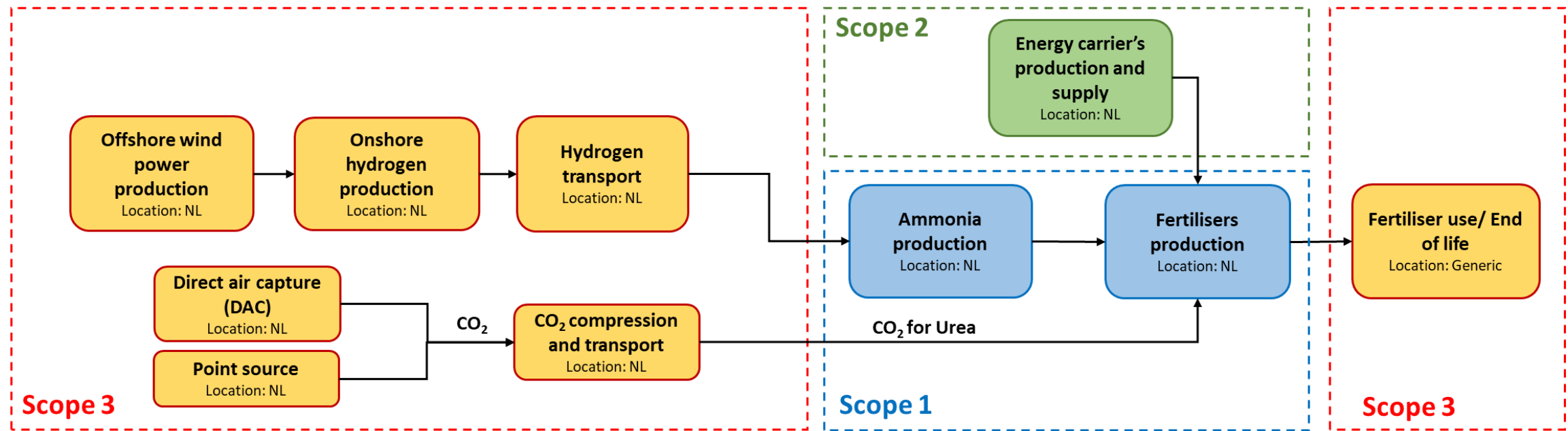


Figure 14. Alternative option 1-fertilisers production using locally produced ammonia

THE SUPPLY CHAIN OVERVIEW: ALTERNATIVE CASES

SUPPLY CHAIN DIAGRAM & MAIN ASSUMPTIONS

- Option 2 focuses on imported ammonia. Literature indicates that imported ammonia is one of the preferred options, both from a cost/price perspective and a safety perspective when compared to H₂ import for local ammonia production (HyDelta, 2022). The total ammonia production capacity in the Netherlands is large (annual production capacity is around 3 Mtonne). Therefore, these facilities are assumed to be (partially) decommissioned and replaced by ammonia imports. Like the previous option (1), option 2 requires an air separation unit to supply N₂ to produce ammonia.
- In the conventional process, a fraction of the CO₂ released in the steam methane reforming step (SMR), is used as feedstock for the production of urea. To produce urea, the alternative production routes (Option 1 and 2) require external CO₂ from a different source. Two sources are considered: 1) CO₂ from a point source, 2) CO₂ from direct air capture (DAC). Main assumptions used in this case study can be found in Annex II.
- The functional unit is set to 1 kg N₂ to facilitate consistent comparisons with other studies that analyse fertiliser production. The functional unit includes production, use and end-of-life.

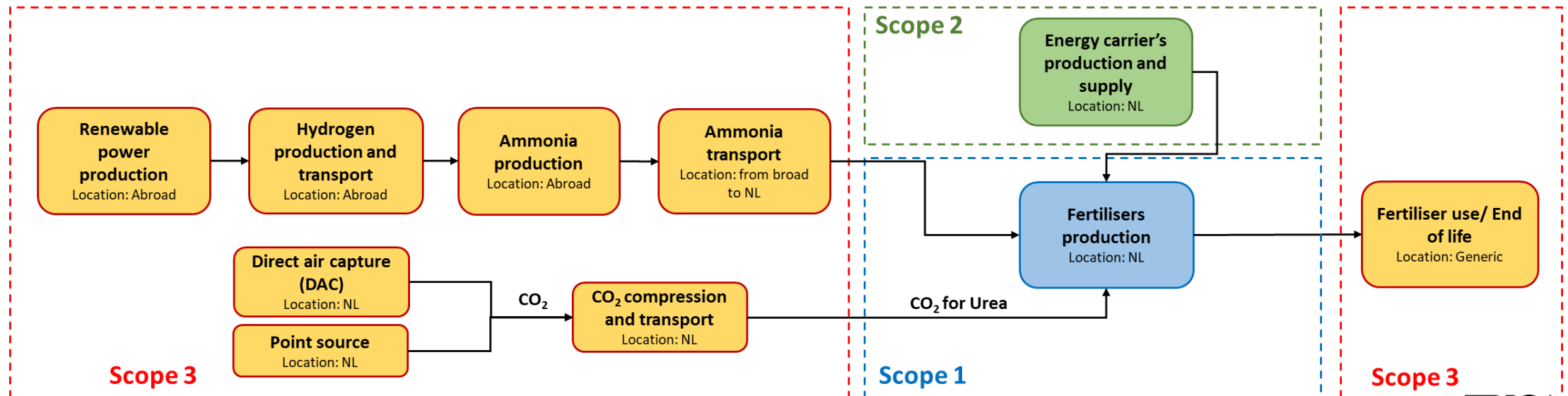


Figure 15. Alternative option 2- Fertilisers production using imported ammonia

RESULTS

COMPARISON OF ALTERNATE CASES WITH FOSSIL-BASED REFERENCE (CRADLE-TO-GATE)

- › Cradle-to-gate fertiliser production emissions can be reduced by 65-80% when compared with the conventional, fossil-based, fertiliser production. Thus, producing fertilisers with renewable H₂, regardless of location and CO₂ source (Point source vs DAC), results in lower GHG emissions over the entire supply chain up to the factory gate.
- › Alternative value chains with CO₂ via DAC appear to have higher emissions than the value chains with the point source CO₂. This is because capturing CO₂ from the air is an energy intensive process and when the electricity from the grid is used this results in high GHG emissions.
- › The lowest emissions are obtained for option 1, where the H₂ is derived from wind energy harvested in the North Sea and the CO₂ is from point source.
- › While ammonia imports may be less costly, the country-specific energy emission factors play an important role for the overall GHG emission performances. This is why the option with the renewable ammonia import from Morocco results in higher GHG emissions.

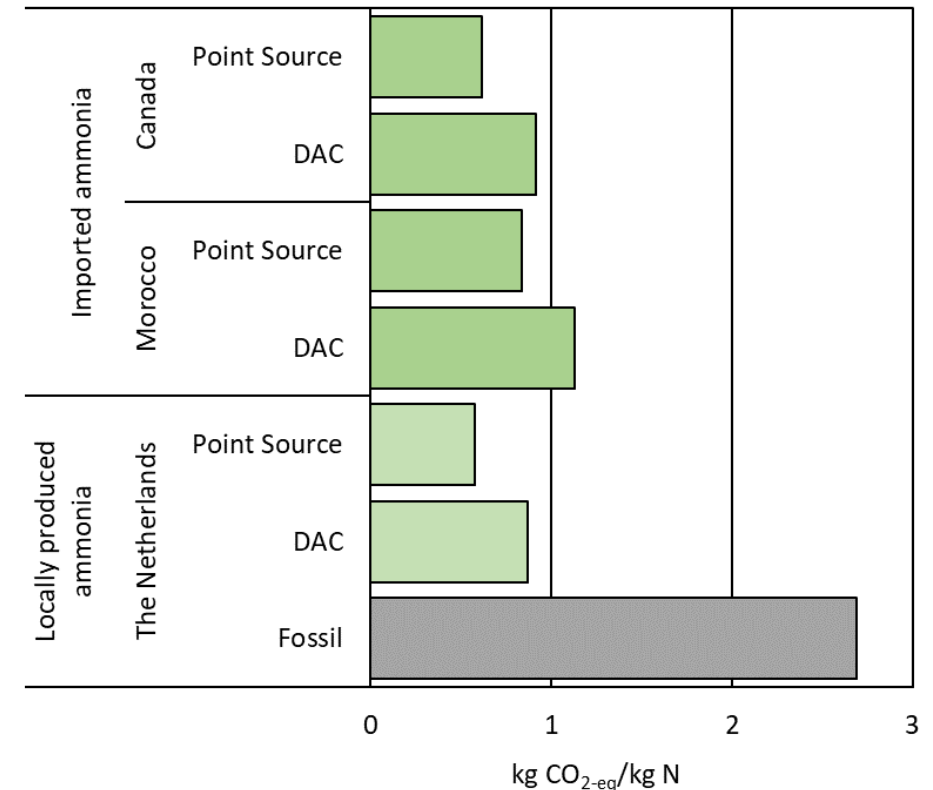


Figure 16. Ranking of fertilizer value chains with renewable H₂ in comparison to fertilizer with fossil-based H₂ (cradle-to-gate).

› RESULTS

GHG EMISSIONS IN THE NETHERLANDS VERSUS ABROAD (CRADLE-TO-GATE)

- › Importing ammonia from abroad lowers the GHG emissions in the Netherlands. However, this may result in higher emissions elsewhere unless low carbon or renewable energy sources are used not only for H₂ production but also for CO₂ capture and the production of ammonia.
- › In this specific case study, the carbon intensity of the grid electricity in the Netherlands was lower than Morocco. Therefore, the value chain emissions for the Moroccan case study was higher.
- › Canada had a lower electricity grid carbon intensity than the Netherlands. Nevertheless, the ammonia transport emissions offset the GHG emission savings in the ammonia production stage, resulting in higher overall GHG emissions.

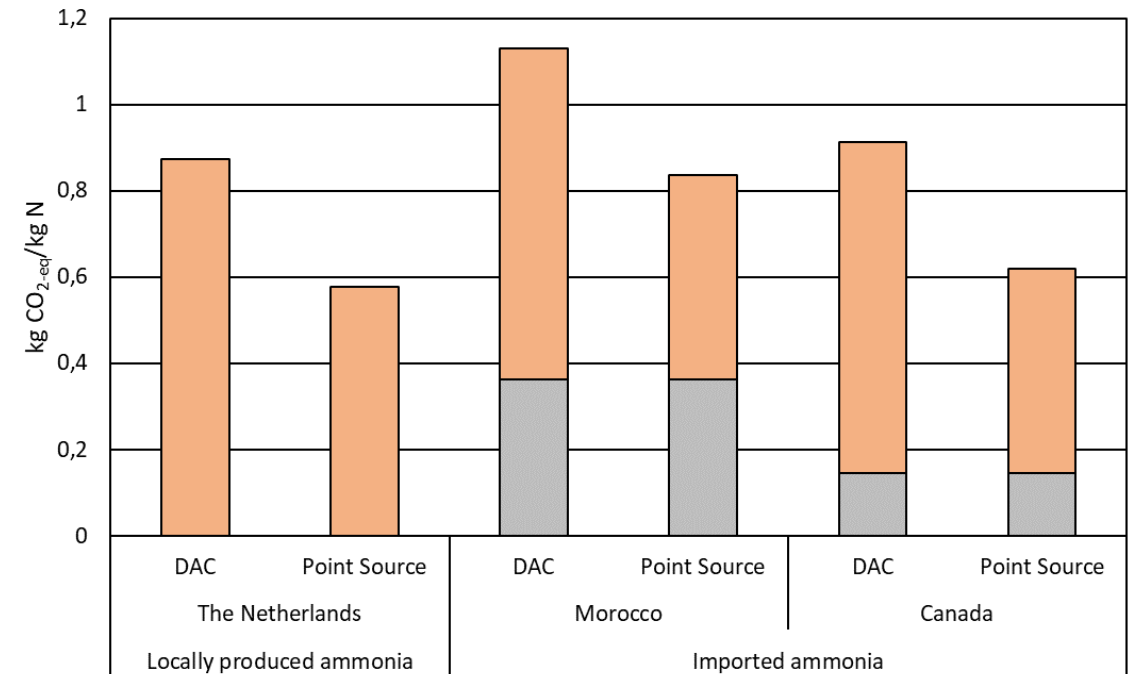
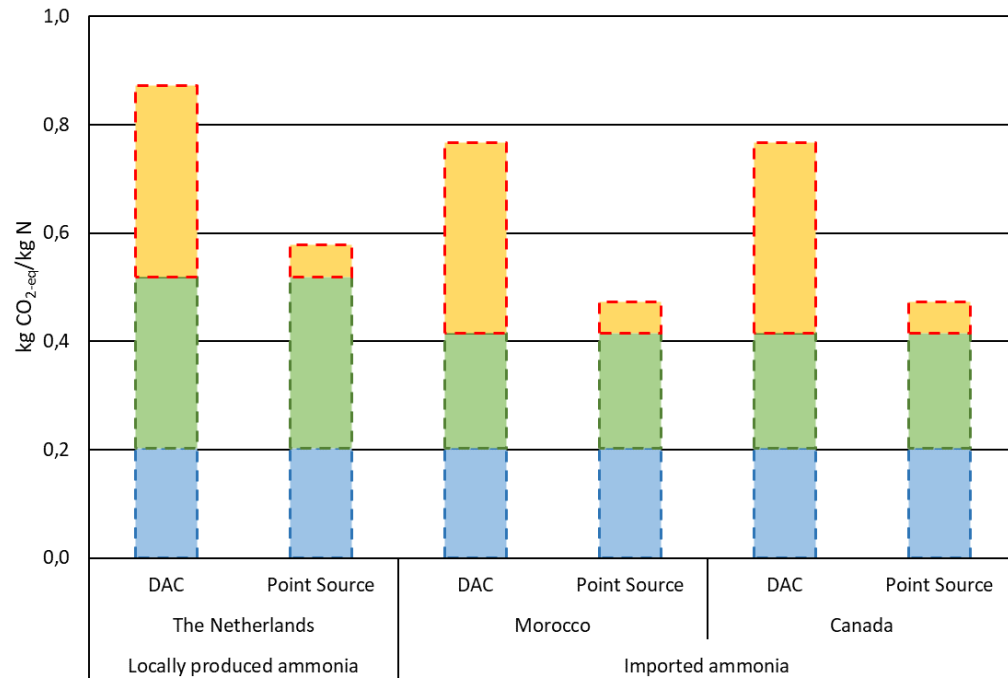


Figure 17. Ranking of fertiliser value chains related to the location of GHG emissions between the Netherlands and abroad

RESULTS

GHG EMISSIONS SCOPES AND SUPPLY CHAIN STAGES

Table 3. GHG emissions of fertiliser production broken down to different scopes



	Locally produced ammonia		Imported ammonia				
	The Netherlands		Marocco		Canada		
	DAC	Point source	DAC	Point source	DAC	Point source	
Scope 3	Hydrogen transport	0,001	0,001	0,001	0,001	0,001	0,001
Scope 2	Ammonia production (air separation unit)	0,07	0,07	0,00	0,00	0,00	0,00
	Ammonia production (electricity)	0,03	0,03	0,00	0,00	0,00	0,00
Scope 3	Ammonia production (air separation unit)	0,00	0,00	0,21	0,21	0,05	0,05
	Ammonia production (electricity)	0,00	0,00	0,10	0,10	0,02	0,02
	Ammonia transport	0,00	0,00	0,05	0,05	0,07	0,07
	CO ₂ capture and supply	0,32	0,02	0,32	0,02	0,32	0,02
Scope 2	Urea production (heat and electricity)	0,16	0,16	0,16	0,16	0,16	0,16
	Nitric Acid production (heat and electricity)	0,01	0,01	0,01	0,01	0,01	0,01
Scope 1	Nitric Acid production (N ₂ Oemissions)	0,20	0,20	0,20	0,20	0,20	0,20
Scope 2	Ammonium Nitrate production (heat and electricity)	0,03	0,03	0,03	0,03	0,03	0,03
	Urea Ammonium Nitrate production (heat and electricity)	0,01	0,01	0,01	0,01	0,01	0,01
	Calcium Ammonium Nitrate production (heat and electricity)	0,01	0,01	0,01	0,01	0,01	0,01
Scope 3	Calcium Ammonium Nitrate production (CaCO ₃)	0,01	0,01	0,01	0,01	0,01	0,01
Scope 2	Ammonium Sulphate production (heat and electricity)	0,004	0,004	0,004	0,004	0,004	0,004
Scope 3	Ammonium Sulphate production (H ₂ SO ₄)	0,03	0,03	0,03	0,03	0,03	0,03
	Use-phase	6,43	7,15	6,43	7,15	6,43	7,15
	Total without use phase	0,87	0,58	1,13	0,84	0,91	0,62
	Total withuse phase	7,31	7,73	7,56	7,99	7,35	7,77

* Units kg CO_{2-eq}/kg N

* Total CO_{2-eq} emissions with the use-phase (Scope 3) are displayed in the secondary y-axis for scale purpose

Figure 18. GHG emissions of fertiliser production broken down to different scopes

› RESULTS

GHG EMISSIONS SCOPES AND SUPPLY CHAIN STAGES

- › While decarbonising ammonia supply results in around 65-80% GHG emission savings, when compared with conventional fossil fertiliser production, the full value chain GHG emissions saving are around 20-25% due to the significant emissions generated during the fertilisers use phase, where N₂O is released. Table 3 introduces the total GHG emissions with and without use phase.
- › The conventional fossil reference scope 1 emissions consists of CO₂ released during H₂ production from natural gas and the N₂O release during the nitric acid production process and while renewable ammonia avoids the release of CO₂, N₂O related scope 1 emissions remain unchanged.
- › Up to the factory gate, and for DAC cases, scope 3 emissions contribute to almost half of the total GHG emissions. These high emissions relate mostly to the capture of CO₂, and the emission factor of the grid electricity.
- › Among the scope 2 emissions of the alternative cases, urea and ammonia production contribute the most. These emissions are generated through the use of heat and electricity. The present emission factors for the Netherlands are implemented. Should renewable energy sources be used, these emissions can be avoided.
- › Fertilisers use phase emissions vary between 6.43 and 6.97 kg CO_{2-eq} / kg N and contribute to almost 90% of the overall emissions, thus, scope 1 and 2 emissions becoming minor within the full value chain emissions.
- › It is necessary to note that the calculation of use phase GHG emissions is very complex. While the IPCC default values are used in this study, the IPCC provides a very wide range of potential emission factors. The N₂O emissions will depend on, amongst other things, the location, crop type, climatic conditions and the agricultural management practices used.

› CONCLUSIONS AND LIMITATIONS

- › Decarbonising the ammonia supply to produce fertilisers can significantly reduce GHG emissions compared to conventional fertiliser production via steam methane reforming. However, direct emissions related to N_2O release during the nitric acid production process stays unchanged, which is a strong greenhouse gas.
 - › The EU ETS benchmark is set to $0.974 \text{ kgN}_2\text{O}/\text{tHNO}_3$. This study, however, used a lower emission factor as a good representation for the Netherlands (Batool & Wetzels, 2019). This value is between the range of the EU best available technique (BAT) for existing nitric acid production plants, which is given as $0.12\text{-}1.85 \text{ kgN}_2\text{O}$ (Fertiliser Europe, 2019)
- › Up to the factory gate, the production of fertilisers in the Netherlands with renewable H_2 offers a better GHG emissions performance in comparison to renewable ammonia supply from other countries. This performance can potentially increase even further with the decarbonisation of energy sources in line with the European Green Deal. The GHG emissions performance of alternative value chain based on renewable ammonia import can also be improved when renewable electricity is used not only for H_2 generation but also to capture CO_2 and during the ammonia production process, and can contribute to significant GHG emission reductions as the transport related emissions from importing renewable ammonia are very small.
- › The CO_2 needed for urea production is assumed to be supplied either from a point source or from DAC. While the point source CO_2 emissions are accounted for at the use phase as they have a fossil origin, CO_2 emissions via DAC are assumed to be zero.
- › According to the draft Delegated Act from the commission on GHG methodology for renewable fuels of non biological origin (RFNBO) the origin of carbon used is not relevant for determining emission savings in the short to medium term, as plenty of carbon sources are available and can be captured. Capturing of emissions from non-sustainable sources should be considered as avoiding until 2041 (C(2023)1087 final)
 - › Following this approach, thus assuming that the point source CO_2 is counted as zero, this does not change the overall results as the contribution of urea use to the overall emissions is very limited. The results change by only 7%. This is because the total amount of urea production is small in comparison to the nitrogen fertilisers and the global warming potential of N_2O is very high.

› CONCLUSIONS AND LIMITATIONS

- › Direct and indirect (N₂O) emissions from fertiliser application (use-phase) are included in this assessment. However, these GHG emissions are highly uncertain given that they depend upon different variables such as biophysical conditions (climate, soil characteristics, etc.), crop type, and agricultural practices used. Annex II presents the implemented default values and the wide ranges included in IPCC.

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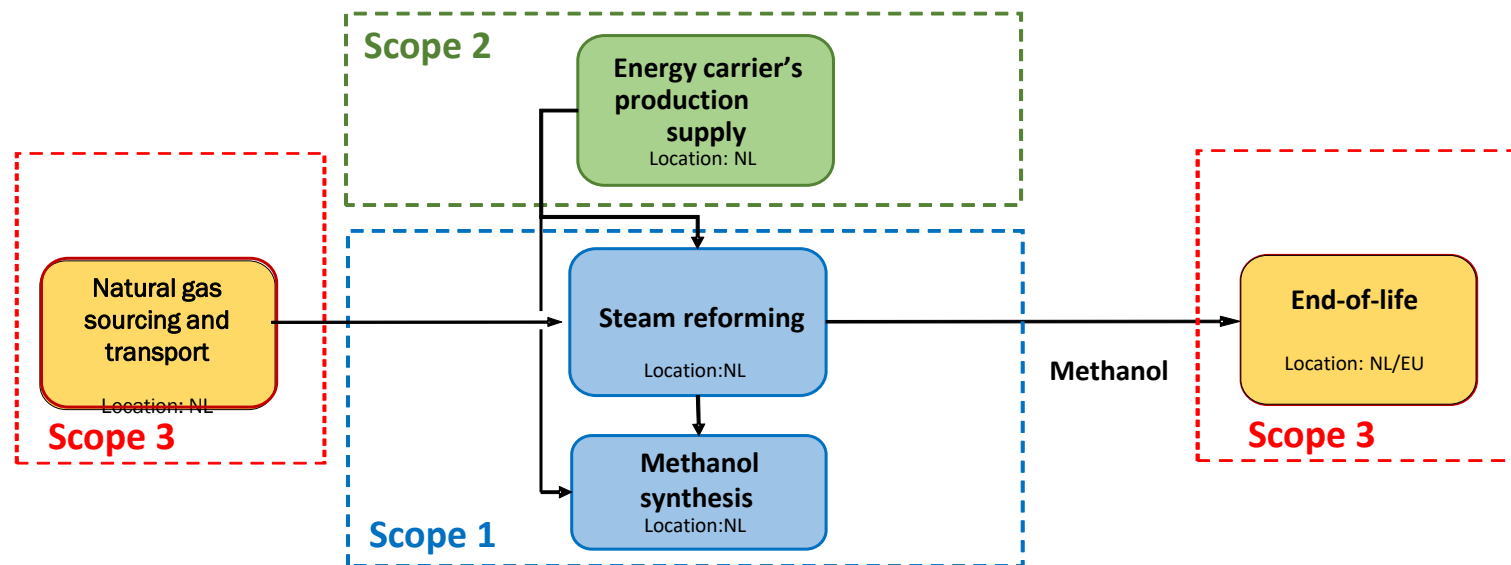
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› METHANOL VIA RDF GASIFICATION

INTRODUCTION

BACKGROUND AND OBJECTIVES

- › Methanol is an essential building block in the chemical sector for the production of different chemicals, such as solvents and components that are further converted into plastics. In addition, it is widely used in the transport sector, either as a blending component to gasoline or as feedstock for MTBE (Methyl tert-Butyl Ether blended in gasoline) or FAME (Fatty acid methylene ester blended in diesel) production (IEA, 2018; IEA-AMF, 2022).
- › Methanol is produced mainly via natural gas steam reforming, which converts natural gas into syngas, followed by methanol synthesis. Figure 16 illustrates the conventional methanol reference considered in this study. Companies are currently exploring alternatives for the sourcing of syngas within the methanol production value chain. One of the options explored is the gasification of waste to syngas. This option allows the re-use of carbon and, therefore, it has potential to reduce the total GHG emissions of the methanol production value chain.
- › This case study focuses on methanol production using waste as an alternative to natural gas-based methanol production and use.



*Note on end-of-life of methanol:
It is considered that methanol will be combusted at some point of its life cycle. Carbon embedded in methanol is estimated via stoichiometry from the combustion reaction (1.37 kg CO₂/kg methanol)*

Figure 19. Generic conventional methanol production via natural gas reforming flow diagram showing the system boundaries and the classification of different steps to scope 1, 2 or 3.

› METHANOL VIA RDF GASIFICATION

SUPPLY CHAIN DIAGRAM & SYSTEM BOUNDARIES

- › Figure 20 illustrates the generic flow diagram of the alternative case, where steps are grouped as scope 1, 2 or 3. This considers that both the gasification and methanol synthesis are within the system boundaries of the factory.
- › 1 tonne of methanol is used as the functional unit and the total GHG emissions are allocated to this product using the mass balance. The functional unit includes the production and the end of life.
- › In this case study, refused derived fuel (RDF) is considered as the feedstock. RDF is a homogeneous fuel that is composed of the combustible components from mixed solid waste (MSW), where MSW includes a diverse range of materials. RDF is considered to be a better performing feedstock for the gasification process (Borgogna, A. et al, 2021). Main assumptions regarding the RDF characteristics, the gasification process and the end-of-life assumptions can be found in Annex III.

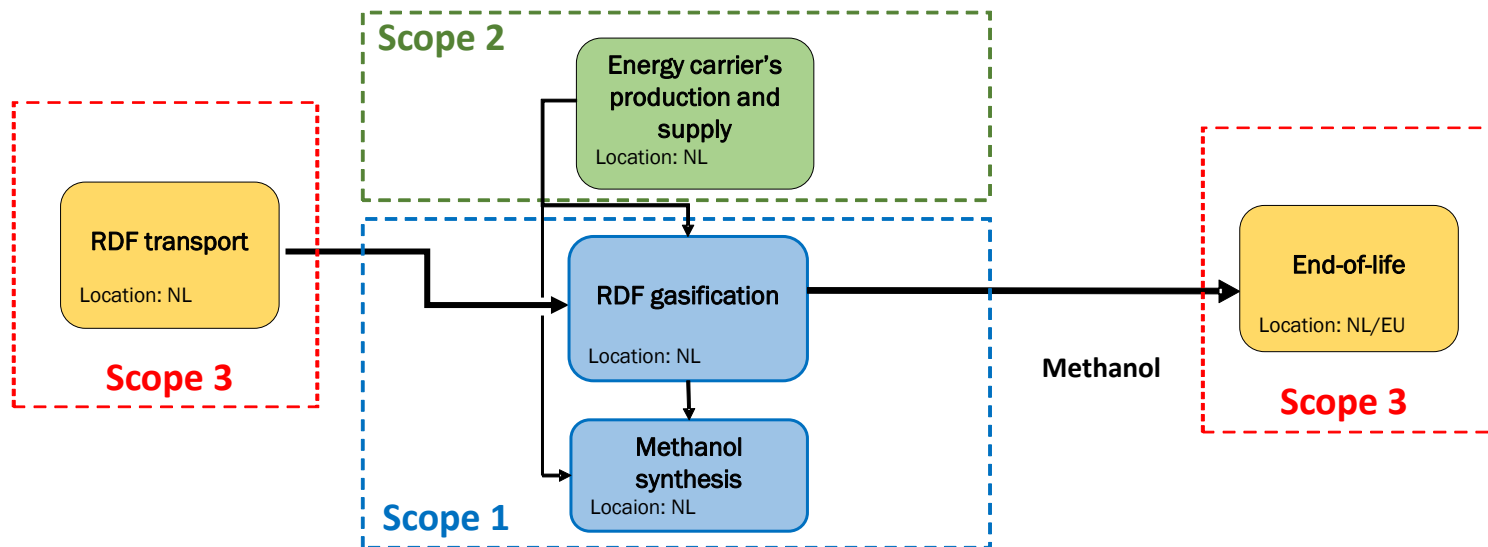


Figure 20. Generic methanol production via RDF flow diagram showing the system boundaries and the classification of different steps to scope 1, 2 or 3. **TNO** innovation for life

RESULTS

COMPARISON WITH FOSSIL REFERENCE

- › Cradle-to-gate methanol production from RDF results in around 130% higher GHG emissions than the fossil reference. This relates to the electricity use for the air separation unit, the steam and natural gas use for the gasification process, and the electricity use during the gasification and methanol synthesis.
- › The higher energy demand in the RDF gasification process can be justified by the multiple reforming operations required in the gasification route, while in the fossil reference a single step for the reforming is needed (Singh, A. et al, 2022).
- › These higher emissions can be reduced when renewable electricity is used to meet the energy demand, the cradle-to-gate emissions reduce 31%, when compared to the baseline value chain that considers electricity from the grid. Compared to the conventional methanol route, the cradle-to-gate emissions of the route with renewable electricity are 60% higher.
- › Contrary to the cradle-to-gate emissions, the full value chain analysis of methanol from RDF results in ~7% lower GHG emissions, compared to the conventional fossil reference. The GHG emission savings increases to ~28% when electricity used during the gasification and methanol synthesis processes are derived from wind (or other renewable) energy sources.
- › The GHG emissions reduction potential relates mainly to the feedstock supply and the end-of-life emissions, which are, respectively, 98% and 67% lower in the gasification value chains.
- › The EoL emissions savings relate to the biogenic carbon content of the methanol produced via gasification, which is calculated as being as zero emissions when released to the atmosphere.

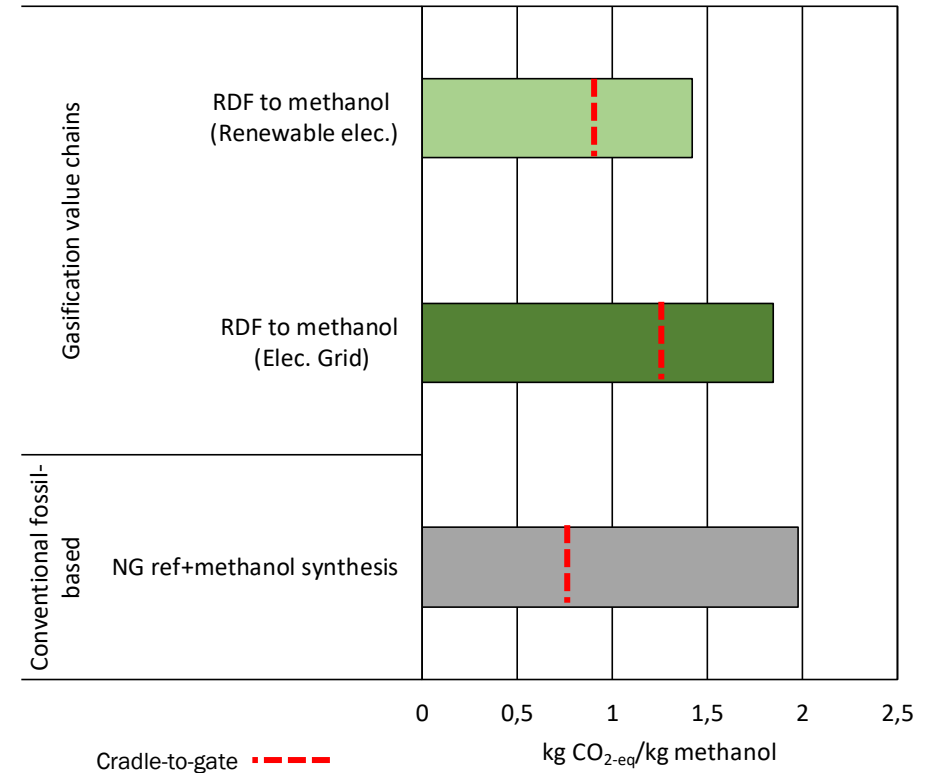


Figure 21. Cradle-to-grave and cradle-to-gate emissions for the conventional methanol production and two alternative gasification routes

*Elec. Grid : electricity demand is provided by the grid, the emission factor for the electricity is 0,25 kgCO_{2eq}/kWh (PBL, 2020).

*Renewable electricity: electricity is sourced by wind turbines, with an emission factor of zero (JRC, 2021).

RESULTS

GHG EMISSIONS SCOPES AND SUPPLY CHAIN STAGES

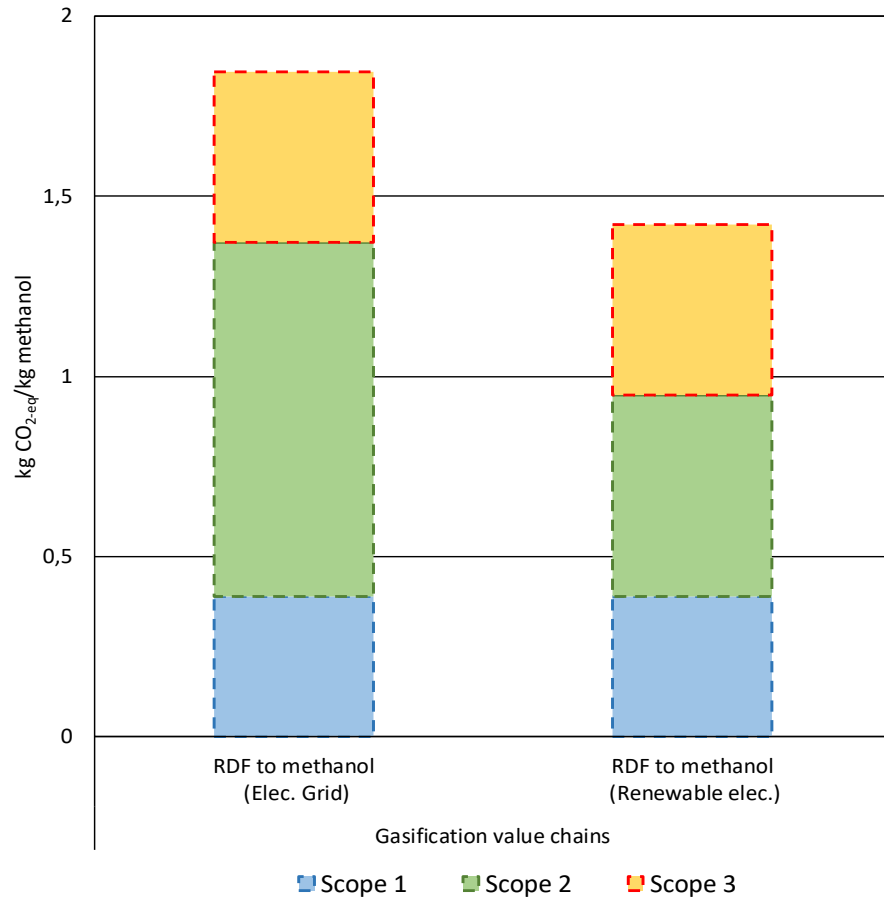


Figure 22. GHG emissions grouped as scope 1, 2 or 3 for both RDF to methanol using electricity from the grid and RDF to methanol using renewable electricity

- Figure 22 and Table 4 show the breakdown of the full value chain emission to different scopes. Scope 2 emissions appear as the largest CO₂ source, representing around 53% of the total GHG emissions. As stated previously, this is mainly due to the energy demand for the ASU unit, the gasification and gas cleaning processes.
- The Scope 2 emissions can be reduced by 43% when the electricity source is renewable energy rather than grid electricity.
- Scope 3 emissions are mainly dependent to the end-of-life emissions, which refer to the fossil CO₂ released during the combustion of methanol. These can be reduced via recycling the products produced from this methanol. Biogenic CO₂ release during combustion is 0,9 kg/kg methanol, which is accounted as zero.
- Scope 1 emissions relate to the direct fossil CO₂ emissions released during gasification. The biogenic CO₂ release during gasification is 0,8 kg/kg methanol and it is also accounted as zero.

Table 4. GHG emissions values grouped as scope 1, 2 or 3 for both MISW to methanol using electricity from the grid and MSW to methanol using renewable electricity

		RDF to methanol (Elec. Grid)	RDF to methanol (Renewable elec.)
Scope 3	RDF transport	0,01	0,01
Scope 2	RDF gasification & methanol synthesis	0,98	0,56
Scope 1	RDF gasification & methanol synthesis	0,39	0,39
Scope 3	End-of life	0,46	0,46
	Total	1,84	1,42

* Units kg CO₂-eq/kg methanol

SENSITIVITY CASE

CO₂ FROM GASIFICATION TO CCS

- › In this sensitivity case, the stream with high concentration of CO₂ leaving the gasification unit is captured, compressed and transported for storage. The efficiency of the capturing system is set as 91% (Lamboos, S., Marsidi, M. en Lensink, S., 2021).
- › The biogenic CO₂ released from the gasification system is around 0,07 kg/kg methanol.
- › Figure 23 shows the comparison between the cases, both with and without CCS. It is notable that the total emissions reduce significantly with CCS (49% lower), mainly because of the negative scope 1 emissions. This negative value is a result of storing biogenic carbon. Although the scope 2 and scope 3 emissions increase slightly due to the CO₂ compression for capturing and storage, the effect is minor compared with the impact of the scope 1 emissions.
- › When comparing the RDF to methanol with CCS case to the fossil reference, the total emissions reduction is around 53%.

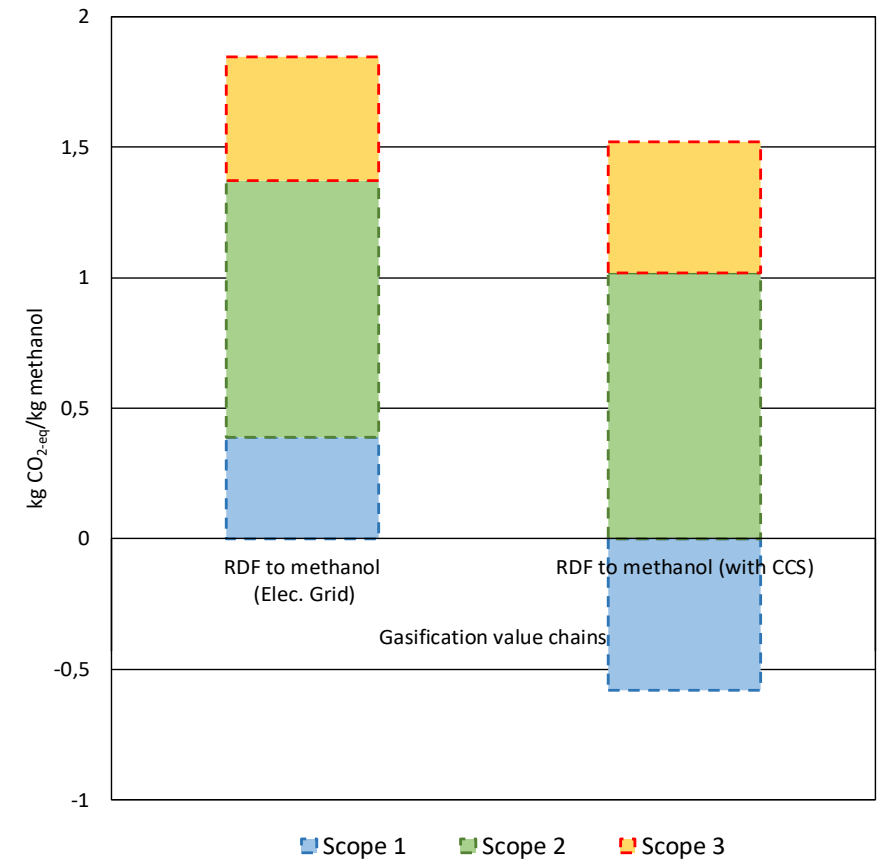


Figure 23. GHG emissions grouped as scope 1, 2 or 3 for both RDF to methanol with and without CCS

SENSITIVITY CASE

HIGHER CARBON EFFICIENCY GASIFICATION

- › In this sensitivity case, the carbon efficiency towards methanol is increased from 32% to 40% by wt.
- › This value refers to how much carbon (from the total input) is allocated in the main product methanol and not lost in the other streams, such as waste water, CO₂ pure and flue gases.
- › When the efficiency increases, the losses via CO₂ pure and flue gases is lower, which reduces the scope 1 emissions by 35%.
- › The overall GHG emissions (cradle-to-grave) reduces by 8%, when compared with the RDF to methanol base case and ~ 14%, when compared with the natural gas-to-methanol value chain.
- › In the higher carbon efficiency case, the biogenic CO₂ released via gasification is around 0,5 kg/kg methanol, compared to 0,8 kg/kg methanol from the case with lower carbon efficiency.

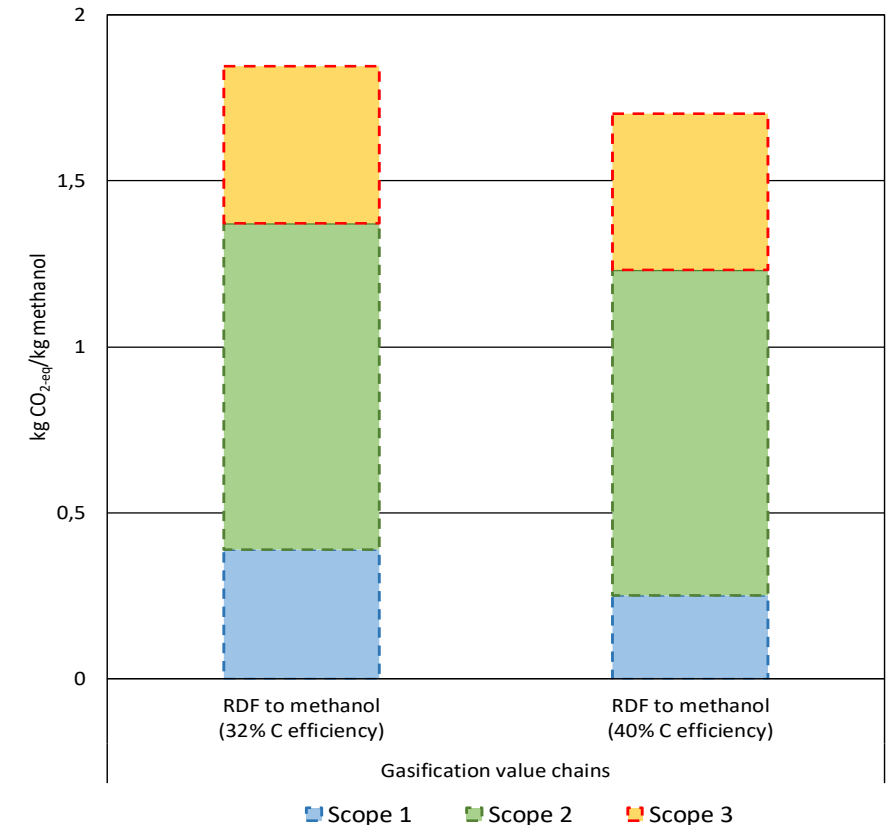


Figure 24. GHG emissions grouped as scope 1, 2 or 3 for RDF to methanol value chain for different carbon efficiencies

SENSITIVITY CASE

MIXED SOLID WASTE CONVERSION TO RDF

- › In this sensitivity case, the system boundary also includes the collection and treatment of mixed solid waste (MSW) to RDF prior to the gasification process.
- › The emissions related to the transportation of MSW to the treatment facility and the electricity consumption* for the process are included in the calculation.
- › The MSW treatment is composed of machinery steps, which separates materials with high calorific values from materials with lower calorific value. The high calorific materials are pelletized into refuse-derived fuel (RDF). Around 54% wt of the total MSW is converted to RDF (Pressley et al, 2014).
- › The residual material is assumed to be incinerated, however, the organic portion is estimated to be around 56% (mass basis), see Annex III. Therefore, part of the GHG emissions impact from the incineration process is zero. During the incineration process, heat and electricity are also considered to be recovered.
- › The overall GHG emissions (Cradle-to-grave) are around 0,5% higher in the alternative value chain where MSW transport and treatment are included in the system boundaries. The scope 3 emissions are 3% higher, specially due to the incineration of the residual material.
- › If different compositions for the MSW and residual material are considered, the results can change significantly. For instance, if the organic composition of the residual material is around 60% (LHV basis), the overall GHG emissions (Cradle-to-grave) reach the same value as the conventional fossil-based reference.

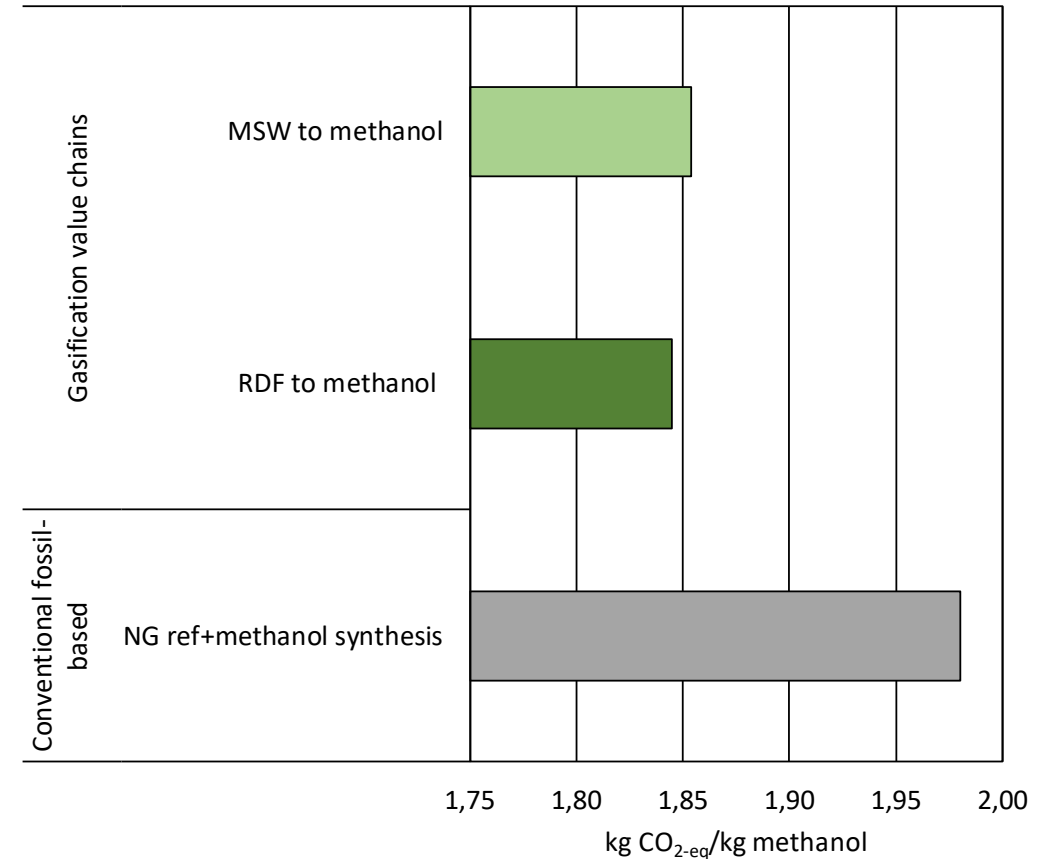


Figure 25. Cradle-to- grave emissions for the conventional methanol production and two alternative gasification routes

*Electricity consumptions considered to be 1,55 kWh/t MSW (Pressley et al, 2014)

› MAIN CONCLUSIONS AND LIMITATIONS

- › Methanol production using RDF is an energy-intensive process and results in higher GHG emissions when compared with the natural gas-to-methanol value chain, when looking at the cradle-to-gate emissions. The gasification process is not fully commercialized and future improvements may increase the conversion efficiency. In addition, the use of renewable electricity improves the GHG emissions performance.
- › However, when the full value chain emissions are considered, including the end-of life, methanol production using RDF reduces overall GHG emissions, mainly thanks to the biogenic carbon share of the RDF, as the GHG emissions impact of biogenic carbon release is assumed to be zero.
- › Another important conclusion relates to the fact that the waste that cannot be mechanically recycled is converted to a methanol intermediate, which can be used to produce other chemicals, such as feedstock for plastics production (olefins). Thus, the benefits of recycling is reflected by allocating zero emissions to RDF.
- › The addition of CCS to the gasification unit could improve significantly the total GHG emissions profile of the RDF gasification value chain, mainly due to potential of capturing and storing biogenic carbon, allowing negative emissions. However, this alternative is very dependent of the site's access to CO₂ transport infrastructure.
- › The traceability of the biogenic carbon present in RDF throughout the value chain was not explored. The simplified approach of considering the same biogenic content for both RDF and the final product (methanol) is a limitation of this study, therefore, further attention to biogenic carbon allocation should be given in future studies.
- › The composition considered for this study is based on only Dutch RDF, no RDF import was considered and the data related to its composition is from source is outdated, which is also a limitation of this study.
- › The natural gas-to-methanol reference is based on the EU average, based on emissions calculations from JRC for a typical methanol production site. Thus, it does not represent specifically the Dutch circumstances.

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FINAL TAKE AWAY MESSAGES

› TAKE AWAY MESSAGES

- › It is vital to focus on full value chain GHG emissions (including scope 2 and scope 3) and not only on the performance of scope 1 GHG emissions in industry innovations. Therefore, policy design should aim at reducing the overall value chain GHG emissions.
- › Using renewable electricity should be prioritised for the direct electrification of steam crackers. Furthermore, substituting fossil naphtha with renewable and circular options should be incentivized.
- › Reducing GHG emissions in fertilisers value chains requires shifting to renewable ammonia production and use, and good agricultural practices that aim to reduce direct and indirect N₂O emissions.
- › The RDF to methanol value chain results in limited GHG emissions savings when the methanol is assumed to be combusted. However, different options should be explored as they will improve the overall value chain GHG performance. For example, using methanol as a building material for the chemical industry (store of biogenic carbon) coupled with recycling options at the end-of-life.
- › All the assessed innovations are relevant to reducing scope 1 GHG emissions in the Netherlands. However, substituting fossil feedstocks with renewable and sustainable resources and reducing scope 3 emissions remain one of the industry's main challenges.

ANNEXES

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› ANNEX I - ELECTRIC CRACKING

› **ELECTRIC STEAM CRACKING**

MAIN ASSUMPTIONS – RESIDUAL FUEL GAS USE

- › Direct electrification of cracking process results in fuel gas becoming available for other uses. Fuel gas is usually rich in methane, around 95%vol. (Internal communication with companies, 2022), however, the composition may vary between different sites. It is assumed that H₂ will be produced from this available gas using ATR technology, followed by CCS. ATR is a preferred technology to produce pure H₂ and allows capture of carbon at higher rates, when for instance, compared with the conventional steam methane reforming (SMR) (Lamboos, S. et al., 2021).
- › It is assumed that this ATR will be located close to the cracker unit because of possible presence of condensable chemicals in the fuel gas, which might create problems to transfer such stream via pipeline over long distances. This means that the ATR falls within the system boundaries of the steam cracking facility, therefore, its direct CO₂ emissions are classified as scope 1 and the energy demand of the ATR and the carbon capture processes are classified as scope 2 emissions (See Figure 3).
- › The fuel gas is assumed to have the same performance as natural gas in the ATR system. For 1 kg of H₂ production around 8.1 kg CO₂ is assumed to be captured, this number is based on 91% capture efficiency (Lamboos, S. et al., 2021). The captured CO₂ is compressed (to 22 bar) on site and transported via a pipeline to the storage location, where an interim compression (to 35 bar) is achieved just before storage. The CO₂ compression levels are based on the SDE++ concept advice for CCS with gas transport, where the Porthos transport network is expected to operate under 35 bar (Lamboos, S. et al., 2021).
- › The blue H₂ produced can be sold to third parties. This end-use is not explored in the assessment due to the chosen mass allocation approach to ethylene. Nevertheless, this stream can be used, for instance, as feedstock in hydrotreatment processes of refineries and other chemical facilities.
- › The same end-of life options for ethylene are considered for this case study and for the conventional reference. This approach is chosen because the application of an electric cracking system does not influence the use and end-of-life of the cracking products.

› **ELECTRIC STEAM CRACKING**

MAIN ASSUMPTIONS – HEAT DISTRIBUTION AND ELECTRICITY INPUT

- › In the conventional steam cracking system, a significant amount of heat is recovered (via steam production) from the hot cracked gas and the exhausted gases, and used to cover the heat demand of compressors and downstream processes (e.g. products recovery via distillation).
- › The heat integration of a typical steam cracking unit is highly complex. In this case study, in discussion with the industrial players, we assumed that not only the heat demand of furnaces but also the compressors will be fully met by electricity. Although the compressors are considered to be electric, the steam demand in downstream units is kept the same as in the conventional value chain, and the heat recovery is adjusted to meet their specific steam demand.
- › The heat distribution in a conventional steam cracker is estimated based on the interviews with chemical companies (SABIC and Shell) and this served as a basis for estimating the changes on heat input and distribution in an electric cracking system. The electricity input in the electric cracking value chain is based on the heat demand for feedstock pre-heating, for cracking reactions in the furnaces and for the compressors shaft work.
- › Regarding the new value chain mass balance, little is known about how the cracking reactions could be affected by electric heating. Companies and universities are still investigating the possible changes, thus, limited literature is currently publicly available. Therefore, it is assumed that the proposed value chain presents the same feedstock input (naphtha) and product yields as in the conventional steam cracking system.

› **ELECTRIC STEAM CRACKING**

MAIN ASSUMPTIONS – END-OF-LIFE (EOL)

- › Three different options are implemented in the electric cracking case study to cover the possible range of EoL scenarios that may occur in the Netherlands or abroad.
 - › Option 1: Incineration assumes that all possible products containing the equal amount of produced ethylene are incinerated with energy recovery and the carbon embedded in the products are released. Heat and power efficiencies are assumed as 6% and 21% respectively (Schwartz, A.E. et al., 2020). Carbon embedded in ethylene is estimated by stoichiometry.
 - › Option 2: Mechanical recycling assumes that a certain fraction of ethylene-based products that will be mechanically recycled. Not all of the ethylene-based plastics can be collected and recycled, therefore, a 42% collection rate and 71% sorting efficiency (Picuno, et al., 2021) are implemented in this scenario. The remaining rejected fraction, corresponding to around 70% of the total plastic waste, is assumed to be incinerated with energy recovery.
 - › Option 3: Chemical recycling combined with mechanical recycling. In this EoL scenario, the plastic that cannot be mechanically recycled is assumed to be chemically recycled via pyrolysis. The rejected fraction in this option (around 18% of the total waste) are also assumed to be incinerated with energy recovery.
- › For conventional reference, only options 1 and 2 are explored further in this study, as these two options are the most representative for the Netherlands at this point in time.

› ANNEX 1 – E-CRACKING VALUE CHAIN

MASS BALANCE

- › The conventional steam cracking mass balance yields are presented in Table A 1-1. The same material yields are applied to the electric steam cracking system. However, the fuel gas is considered to be used fully internally in the conventional system to provide heat to the furnaces, while in the electric cracking value chain this fuel gas is used in the blue hydrogen production unit.
- › Table A 1-2 shows the fuel gas composition, this data was shared by the companies during the interviews phase and it was used for estimating the LHV and emission factor of this stream.

Input	kg per kg of ethylene
Naphtha	3,17
Outputs	kg per kg of ethylene
Methane-rich gas	0,46
Ethylene	1,00
Hydrogen	0,03
Propylene	0,49
Butadiene	0,15
Butane + butenes	0,21
Benzene	0,15
Toluene	0,10
C8 aromatics	0,08
Other	0,42
Fuel oil	0,09

Component	%wt
Hydrogen	2,41
Carbon monoxide	1,08
Methane	95,75
Ethylene	0,76
Estimated parameters	
LHV (MJ/kg fuel gas)	48,79
Emission factor (kgCO ₂ /GJ _{LHV})	54,82

Table A 1-2. Typical fuel gas from conventional steam cracking composition (internal communication with companies, 2022)

ANNEX 1- E-CRACKING VALUE CHAIN CONVENTIONAL CRACKING FURNACES HEAT DISTRIBUTION

- › The energy input (as fuel gas) for the conventional steam cracking reference is based on the information present in the MIDDEN reports for the Dutch steam crackers, this number is 0,021 GJ/kg ethylene (Wong, L. and Van Dril, A.W.N, 2020; Oliveira, C. Van Dril, A.W.N, 2021)
- › The heat distribution of conventional steam cracking furnaces is based on data from the technology provider KBR, the information was shared during interviews with the companies. Figure A 1-1 summarizes the heat distribution in the furnaces, based on the energy input related to fuel gas. Table A 1-3 shows the detailed information related to the heat distribution.

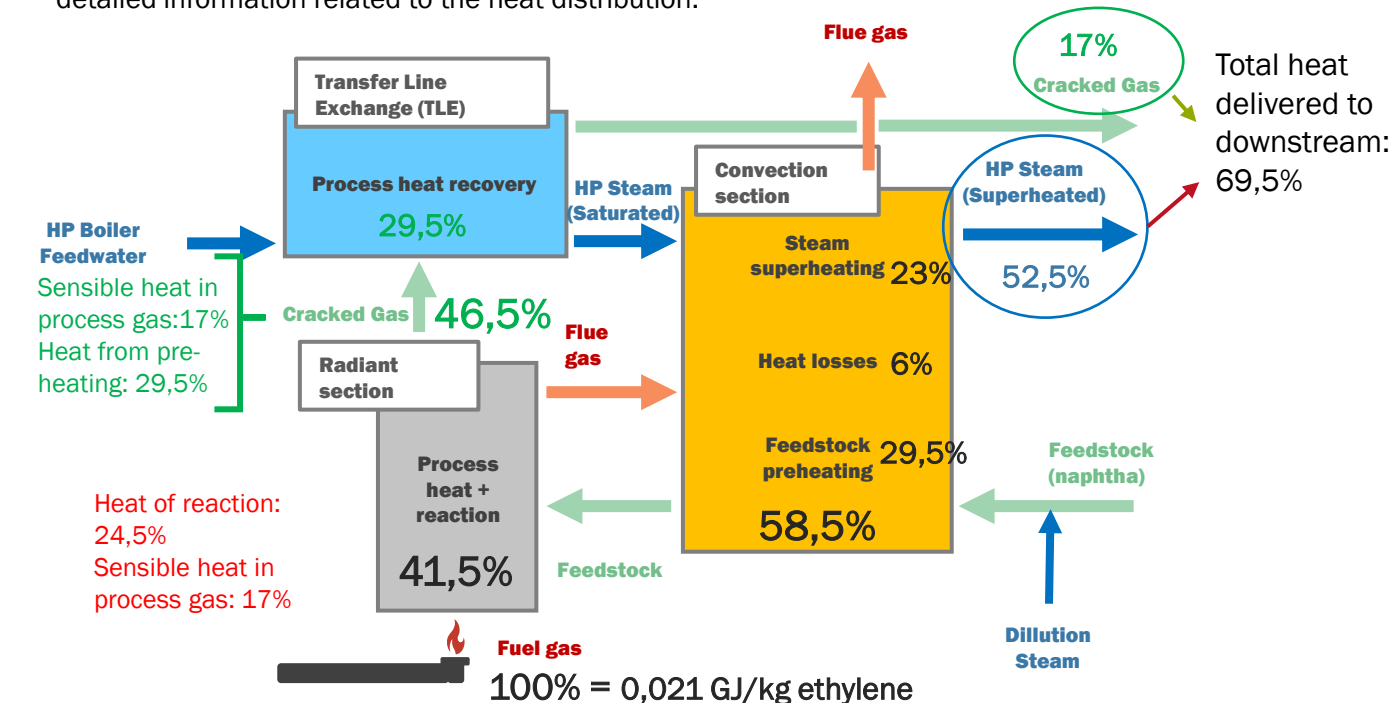


Table A 1-3. Heat distribution in a typical steam cracking furnace (based on KBR, EEPC seminar, 2008)

Conventional furnace - heat distribution		
Total heat input	100	%
To convection section	58,5	%
To radiant section	41,5	%

Radiant section		
Heat of reaction	24,5	%
Sensible heat (process heat)	17	%

Convection section		
Feedstock preheat	29,5	%
Heat recovery	23	%
Losses (stack+walls)	6	%

Heat recovered as SHP		
From TLEs	29,5	%
From convection section	23	%
Total heat recovered as SHP	52,5	%

Process heat recovery		
As superheated high pressure steam	52,5	%
Embedded in cracked gas	17	%
Total heat recovered	69,5	%

Uses of recovered heat		
Major driver (shaft work)	11	%
Dilution steam	10	%
Process use	12,5	%
Process heat recovery as LPS	5	%
Condensate	19	%
Rejected heat	12	%
Total heat use	69,5	%

Figure A 1-1. Heat distribution in a typical steam cracking system (based on KBR, EEPC seminar, 2008)

ANNEX 1- E-CRACKING VALUE CHAIN

ELECTRIC CRACKING FURNACES

HEAT DISTRIBUTION

- › In the proposed e-cracking value chain, both furnaces and compressors are fully electrified. For this reason, the following energy consuming points no longer exist:
 - › Energy losses to the stack (via exhausted gas)
 - › Shaft work from steam turbines of compressors
 - › Steam superheating: since compressors run with electricity, the demand for superheating steam in the system is extinguished
 - › Energy converted to condensate: because compressors are not driven by steam turbines in this value chain, no energy is allocated to condensate streams
- › Because the gas leaving the radiant section (cracked gas) is quite hot also in the e-cracking system, the heat recovery in the TLEs (transfer line exchangers) is kept and part of the heat recovered is used in the pre-heating of feedstock. For this reason, the naphtha pre-heating step is 7% more efficient than in the conventional system (see Table A 1-3 and Table A 1-4)
- › Considering the mentioned above, the estimated heat distribution in the electric cracking system was calculated and the results shows that the heat input in this system is 23% less than in the conventional steam cracking system (difference can be seen directly in total heat input highlighted in the tables A 1-3 and A 1-4)
- › For the electricity demand by the electric compressors, a thermal efficiency of 95% was assumed
- › Figure A 1-2 summarizes the estimated heat distribution in the electric cracking value chain

Electrical furnace - heat distribution		
Feedstock pre-heat	22,5	%
Heat losses (walls)	1	%
Heat of reaction	24,5	%
Sensible heat (process heat)	17	%
Electrical compressors	11,6	%
Total heat input	76,6	%
Recovered heat		
Total remaining heat in cracked gas	17	%
Total heat recovered as steam	22,5	%
Total recovered heat in cracked gas	39,5	%
Uses of recovered heat		
Dilution steam	10	%
Process use	12,5	%
Process heat recovery as LPS	5	%
Losses to ATM	12	%
Total heat use	39,5	%

Table A 1-4. Estimated heat distribution for the proposed electric cracking system

ANNEX 1- E-CRACKING VALUE CHAIN

ELECTRIC CRACKING FURNACES

HEAT DISTRIBUTION

- › Total electricity input to the system
 - › Small equipment: 0,04 kWh/kg ethylene (same as in the conventional steam cracking process)
 - › Electric furnaces: 3,79 kWh/kg ethylene
 - › Electric compressors: 0,68 kWh/kg ethylene

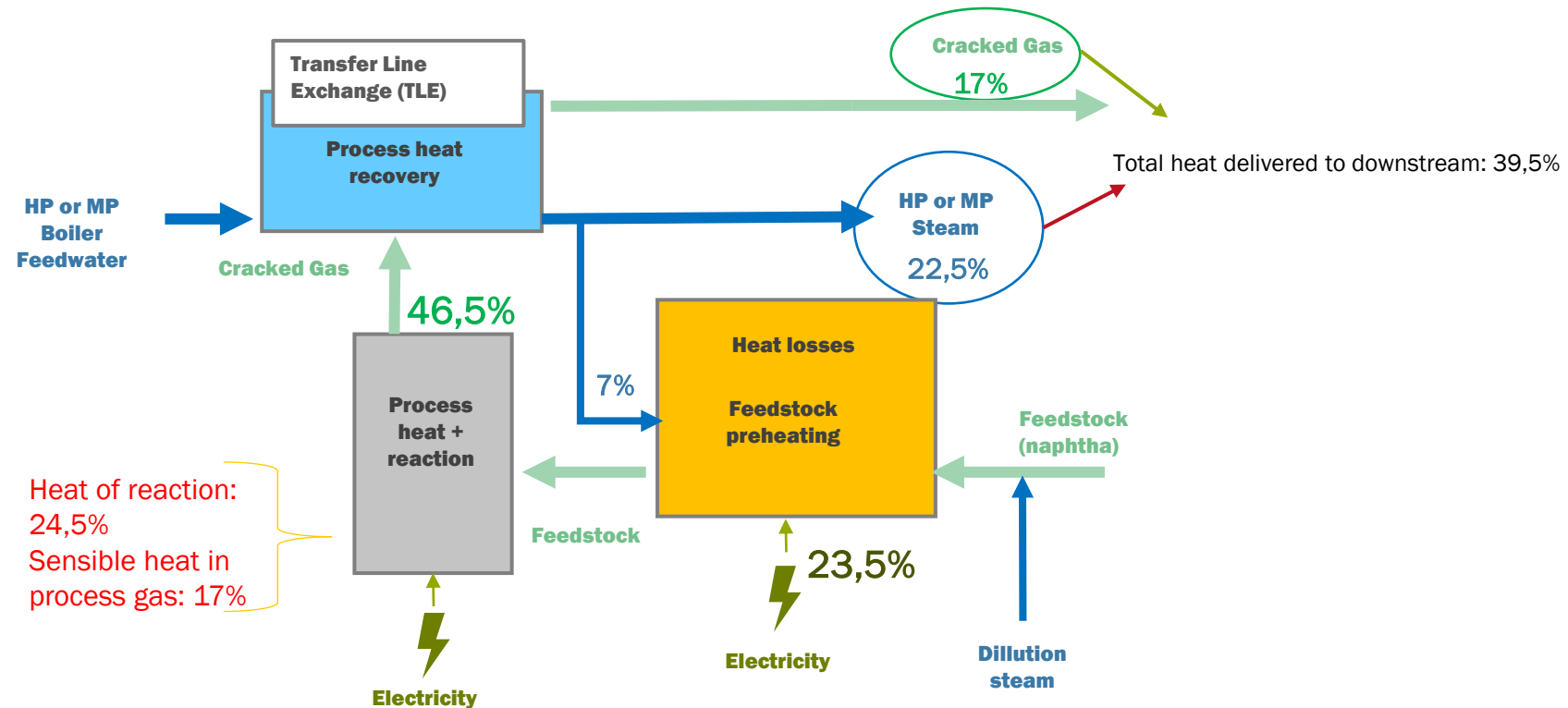


Figure A 1-2. Estimated heat distribution in electric cracking system

ANNEX 1- E-CRACKING VALUE CHAIN

SENSITIVITY CASE - DIFFERENT ELECTRIFICATION LEVEL

Assumptions

- › This sensitivity case considers that only the gas-fired furnaces are replaced by electric furnaces and the compressors are driven with steam turbines, as is the case in the conventional system. This steam demand is supplied by gas boilers using the residual fuel gas from the electric furnaces.
- › The steam demand by the compressors is estimated based on the heat distribution in the conventional system presented by Table A 1-3. The shaft work is 11% of the total heat input and 19% of the total heat input is converted to condensate, therefore, the overall compressors efficiency is estimated to be 37% (see Figure A 1-3). Considering the compressors efficiency, the system's heat input and the overall material balance presented in Table A 1-1, the compressors steam demand is estimated to be 1,75 kWh/kg ethylene.
- › For the steam production via fuel gas boiler, a 80% thermal efficiency is assumed. As presented by Table A 1- 2, the fuel gas LHV is estimated as 48,78 MJ/kg and the emission factor as 54,82 kgCO₂/GJ_{LHV}.
- › With a boiler efficiency of 80%, the total fuel gas input is estimated to be 2,19 kWh/kg ethylene (0,17 kg fuel gas/kg ethylene), leaving 0,30 kg fuel gas/kg ethylene available to be used as feedstock for the blue hydrogen unit.

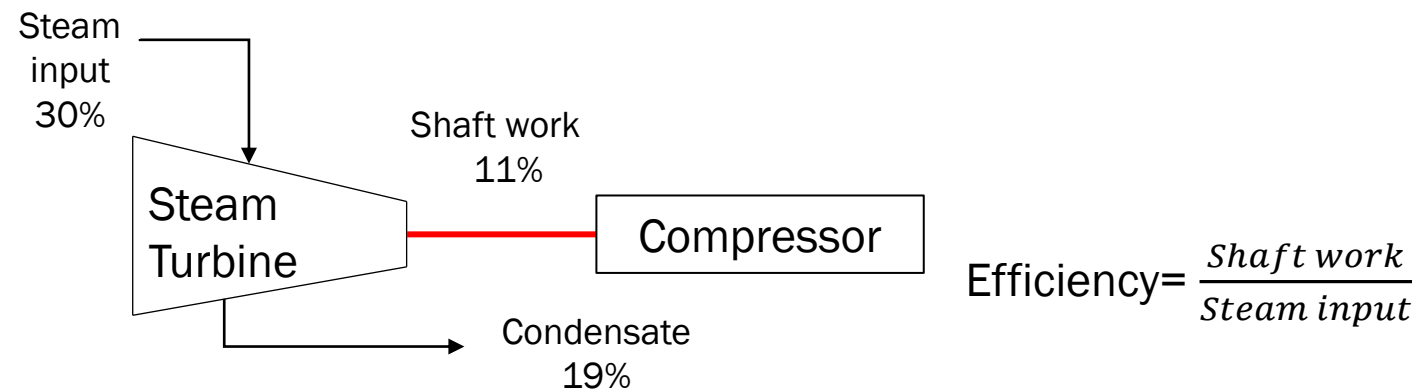


Figure A 1-3. Simplified diagram of compressors energy balance in a steam cracking system

*Not all compressors in a steam cracking system are driven by condensing turbines, therefore, this diagram is a simplification and might not reflect the reality of each site. However, the energy balance presented should be sufficient to represent the overall compression system because it is based on data of the heat distribution in a typical steam cracking system

› ANNEX 1- E-CRACKING VALUE CHAIN EXTRA SENSITIVITY CASE – LIQUID CO₂ TRANSPORT

Assumptions

- › In this sensitivity case, it is considered to transport the capture CO₂ as liquid via trucks to a storage location, therefore, liquification energy requirements are considered in the Scope 3 emissions calculations
- › The storage location considered is where the CO₂ compression station by the PORTHOS initiative is planned (Maasvlakte). The distance considered is 250 km, based on the furthest cracking facility from Maasvlakte
- › The liquification process energy demand is based on the SDE++ Variant 8: new installation; full supply of CO₂ to the CO₂ transport network for CO₂ storage; liquid transportation, which is 162 kWh/t CO₂ captured (Lamboos, S. et al., 2021)

Results

- › CO₂ liquid transport presents almost 2 times more emissions when compared to gas transport
- › However, the impact in total value chain emissions is around 0,8%
- › If storage location is different, impact in total emissions can be more significant

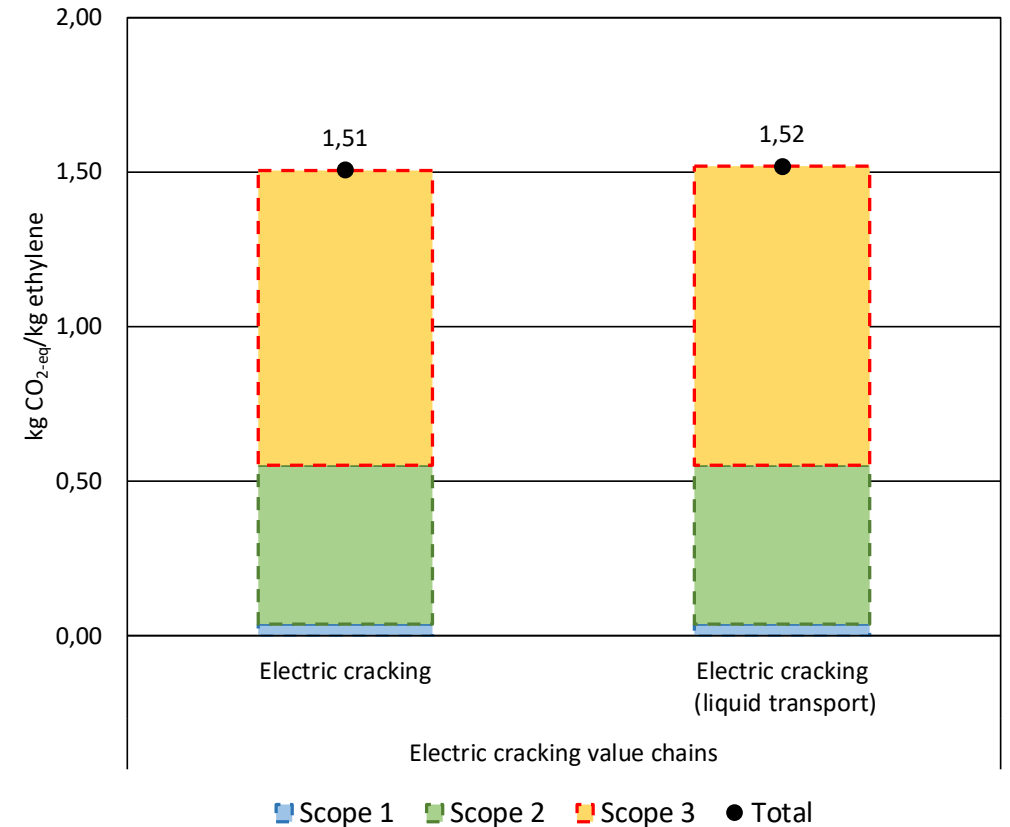


Figure A 1-3 - GHG emissions in different steps to scope 1, 2 or 3 for the for the baseline electric cracking value chain and the extra sensitivity case

› ANNEX 1- E-CRACKING CASE STUDY

EMISSION FACTORS USED

Emission factors	Unit	kg CO2 eq
Natural gas, ROW	1 kg	0,557
Steam	1 kWh	0,226
Wind electricity	1 kWh	0
Electricity, EU27	1 kWh	0,275
Electricity, NL 2019	1 kWh	0,2925
Electricity, NL 2030	1 kWh	0,167
Heat, NL	1 MJ	0,063
Heat, EU 27	1 MJ	0,07
Ethylene EU, average (Cradle-to-gate)	1 kg	1,454
Truck, big 80%LF	1 tkm	0,069
Truck, medium 80%LF	1 tkm	0,174

Table A 1-5. Emission factors considered for the E-cracking case study analysis

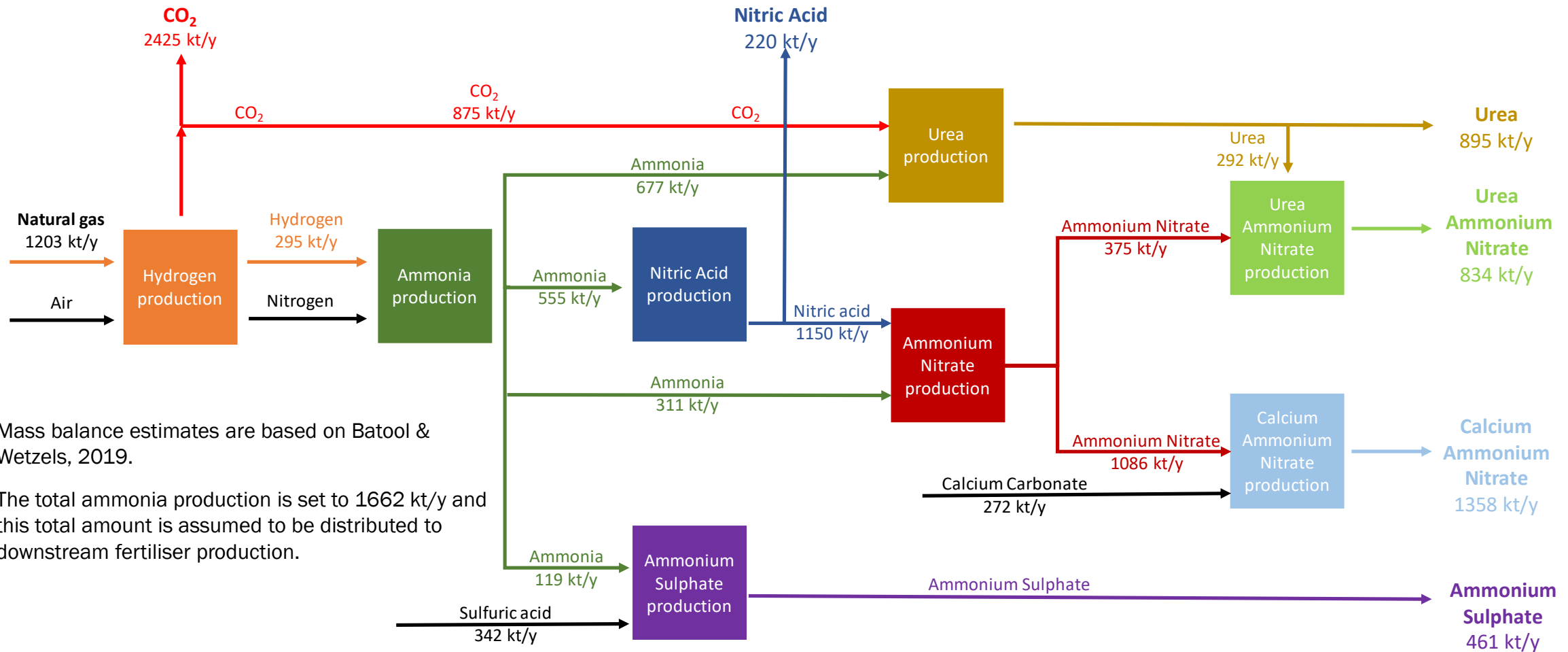
ANNEX II- FERTILISERS CASE STUDY

› MAIN ASSUMPTIONS

- › A generic conventional reference fertiliser production value chain that represents the range of fertilisers produced in the Netherlands is used. The detailed mass flow is illustrated in Figure A2-1.
- › The alternative options assume that the total volume and type of fertilisers produced stay the same as the conventional reference. Option 1 focuses on renewable H₂ production in the Netherlands, whereas option 2 assumes that renewable ammonia will be imported to the Netherlands. Morocco and Canada are selected as the two possible countries from which ammonia can be imported.
- › Country specific emission factors are used. For Morocco and Canada these are derived from JRC (Edwards et al., 2019). For the Netherlands, emission factors are derived from the KEV study (KEV, 2022).
- › Within the fertiliser production process, the nitric acid production process produces N₂O emissions, which have a global warming potential 298 times that of CO₂. The emissions during this process vary significantly from one nitric acid plant to another and depend very much on the site-specific factors, such as plant design, process conditions and abatement technologies employed (GHG protocol, 2022). In this study, the N₂O emission factor of 0.6 kg per tonne nitric acid production is used as a good representation for the Netherlands (Batool & Wetzels, 2019).
- › An in-depth analysis of the use phase is complex. In this study, N₂O emissions from fertilisers used are calculated from IPCC guidelines trier 1 (IPCC, 2019). N₂O emissions from fertiliser use considers direct emissions to the atmosphere and indirect emissions of fertiliser applications to soil (volatilisation and leaching). For these, default emission factors were used and these are presented in Table A2-2 and A2-3. N₂O emissions due to management of soil are not included.

CONVENTIONAL REFERENCE CASE

MAIN ASSUMPTIONS



- › Mass balance estimates are based on Batool & Wetzels, 2019.
- › The total ammonia production is set to 1662 kt/y and this total amount is assumed to be distributed to downstream fertiliser production.

Figure A2-1. Mass balance of the conventional fossil based fertiliser production

ANNEX 2 FERTILISER CASE STUDY

MASS AND ENERGY BALANCE

	Value	Unit
Fertilizer production		
Urea	895	kt/y
Nitric acid	220	kt/y
Urea ammonium nitrate	834	kt/y
Calcium ammonium nitrate	1.358	kt/y
Ammonium sulphate	461	kt/y
Total nitrogen in fertilizer	1.212	kt-N/y
Inputs		
Electricity	1,14	TJ/kg-N
Steam	-2,89	TJ/kg-N
Air	6,69	kg/kg-N
Oxygen	1,51	kg/kg-N
Water	1,49	kg/kg-N
Natural gas	0,99	kg/kg-N
CaCO ₃	0,22	kg/kg-N
Sulfuric acid	0,28	kg/kg-N
Products		
Urea	0,74	kg/kg-N
Nitric acid	0,18	kg/kg-N
Urea ammonium nitrate	0,69	kg/kg-N
Calcium ammonium nitrate	1,12	kg/kg-N
Ammonium sulphate	0,38	kg/kg-N

Table A 2-1. Mass and energy balances for the fertiliser case study

ANNEX 2 FERTILISER CASE STUDY

EMISSION FACTORS USED

Emission factors	Unit	kg CO2 eq
Natural gas, ROW	1 kg	0,557
Steam	1 kWh	0,226
Electricity, EU27	1 kWh	0,255
Electricity, NL 2030	1 kWh	0,167
N ₂ O GWP	1kg	298
CaCO ₃	1kg	0,040
Sulphuric Acid	1 kg	0,096
Pipeline transport	1 tkm	0,060
Truck, big 80%LF	1 tkm	0,069
Truck, medium 80%LF	1 tkm	0,174
Sea, long 80%LF	1 tkm	0,006

Table A 2-2. Emission factors for the fertiliser case study

Emission factors nitrogen emissions due to fertilizer applications				
	Unit	Default	Low end	High End
Direct N- emissions	kg N ₂ O-N/kg N	0,01	0,001	0,018
Indirect N- emissions				
Volatilization - frac volatilized	fraction	0,11	0,02	0,33
Volatilization	kg N ₂ O-N/kg N	0,01	0,002	0,018
Leaching - frac leached	fraction	0,24	0,01	0,73
Leaching - frac leached	kg N ₂ O-N/kg N	0,011	0	0,02

Table A 2-3. Emission factors for the fertiliser case study

ANNEX III- RDF-TO-METHANOL CASE STUDY

› METHANOL VIA MSW GASIFICATION

RDF GASIFICATION – MAIN ASSUMPTIONS

- › Table A3-1 shows the composition of RDF considered for this case study, which is based on the typical RDF from Dutch waste (Phyllis2 database., 2022). The total biogenic content is 66,6% wt. (paper & board, wood, vegetables, fruit and garden waste).
- › The composition of typical Dutch RDF in terms of components, is presented in table A3-2. These values are compared with the composition of the waste feedstock considered by Borgogna et al. (2021) for a production process of methanol via waste gasification (Table A3-3). The main difference relies on the nitrogen content – the Dutch RDF contains 44% more nitrogen than the literature reference. However, the differences in carbon, hydrogen and oxygen content are below 10%, therefore, it is assumed that the gasification of the Dutch RDF has similar yields to those described by Borgogna et al. (2021).
- › For the gasification process, an air separation unit (ASU) is considered within the system boundaries due to the need of high-purity oxygen input. Therefore, the electricity input for the production of oxygen is also taken into account in the assessment. The power consumption of the ASU is based on the range 0.38-0.45 kWh/Nm³ oxygen, which refers to air low-pressure oxygen units (Cryogenmash catalog, access 2022).
- › Both mass and energy balances for the gasification and the methanol synthesis process are based on Borgogna et al. (2021). In which, a yield of 0.51 kg Methanol/kg RDF input is estimated. Further information regarding the energy and mass balances for this value chain can be found below.

Table A3-1. Typical RDF composition from Dutch waste (Phyllis2 database., 2022)

Material	Composition (wt%)
Paper & board	21,9
Wood + vegetables, fruit, garden waste	44,7
Plastics	15,4
Metals	2,6
Other	15,4

Table A3-2. Typical composition by component of Dutch RDF in a dry and ash free basis (Phyllis2 database., 2022)

Component	Composition (wt%, dry and ash free)
Carbon	55,57
Hydrogen	7,39
Oxygen	35,58
Nitrogen	0,88
Sulphur	0,35

Table A3-3. Mixed waste composition by component considered by literature for the gasification process, dry and ash free basis (Borgogna et al., 2021)

Component	Composition (wt%, dry and ash free)
Carbon	58,3
Hydrogen	7,9
Oxygen	32,2
Nitrogen	1,3
Sulphur	0,3

› METHANOL VIA RDF GASIFICATION

METHANOL END-OF-LIFE – MAIN ASSUMPTIONS

- › The use phase of methanol is not detailed in this case study, however it is considered that the methanol would be combusted at the end-of-life independently if the product is used in the chemical sector or in the transport sector. This assumption is similar both for the conventional fossil-based reference and this case study.
- › As mentioned previously, the biogenic content of the RDF fed to the gasification presents around 66,6% of biogenic material. It is assumed that the methanol resulting from the gasification value chain contains the same biogenic content.
- › From the stoichiometry combustion of methanol, the estimated value of methanol is 1.37 kg CO₂/kg. From the total CO₂ release, it is assumed that 66.6% is biogenic and the remaining is fossil-based CO₂.
- › For the reference case, methanol production via natural gas, all the carbon released in the end-of-life is fossil-based.

ANNEX 3 RDF GASIFICATION TO METHANOL CASE STUDY

MASS AND ENERGY BALANCES

Inputs	kg per kg of methanol
RDF feedstock	1,96
Nitrogen	0,15
Oxygen	1,38
Medium pressure steam	0,84
Low pressure steam	1,3
Natural gas	0,037
Cooling water	240,7
Electricity (kWh/kg methanol)	1,1
Outputs	kg per kg of methanol
Methanol	1
Sludge	0,08
Granulated	0,33
Sulphur cake	0,01
CO ₂ , pure	1,07
CO ₂ , - flue gas	0,094
Remaining flue gas	0,72
Waste water (calculated)	2,36

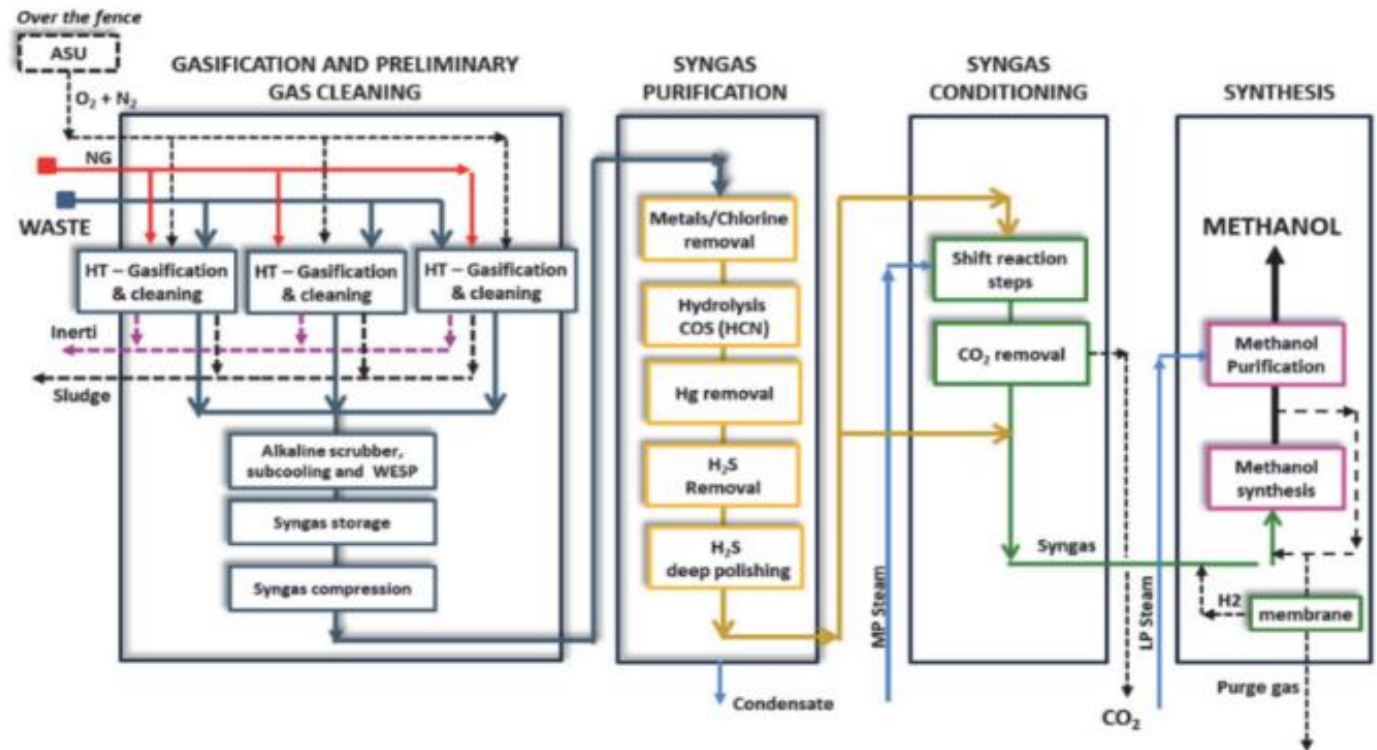


Figure A 3-5. Detailed process flow diagram considered by the literature for estimating the mass and energy balance of the system, extracted from Borgogna et al. (2021)

Table A 3-4. Material and energy flows considered for the RDF gasification to methanol value chain, based on Borgogna et al. (2021)

ANNEX 3 RDF GASIFICATION TO METHANOL CASE STUDY

EMISSION FACTORS USED

Emission factors	Unit	kg CO ₂ , eq
Natural gas, ROW	1 kg	0,557
Steam	1 kWh	0,226
Electricity, EU27	1 kWh	0,275
Electricity, NL 2019	1 kWh	0,2925
Electricity, NL 2030	1 kWh	0,167
Heat, NL	1 MJ	0,063
Heat, EU 27	1 MJ	0,07
Methanol EU, average (Cradle-to-gate)	1 kg	0,603
Truck, big 80%LF	1 tkm	0,069
Truck, medium 80%LF	1 tkm	0,174

Table A 3-6. Emission factors considered for the methanol case study analysis

ANNEX 3 SENSITIVITY CASE MSW GASIFICATION TO METHANOL CASE STUDY

Mixed solid waste	Value
LHV (MJ/kg)	9,8
Emission factor (kgCO ₂ /GJ _{LHV})	105
Organic content (LHV basis)	53%

Table A 3-7. Parameters considered for the MSW (RVO, 2022)

Residual waste	Composition (%wt)	LHV (MJ/kg)
Organic material	43	4,85
Metals	10	0
Glass	22	0
Paper + other material	25*	2,98
Total mixture	-	2,8
Organic content (LHV basis)	87%	-

Emission factor (kgCO ₂ /GJ _{LHV})	105**
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*The composition related to paper + other material is assumed to be 50% organic

**The emission factor is assumed to be the same as MSW.

Table A 3-8. Parameters considered for the residual waste from the MSW conversion to RDF (Composition based on Pressley et al, 2014 and LHV based on Gotze et al, 2016)