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Carbon and climate efficient use of biogenic waste for circular chemicals

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Nyckelord

Avfall, CCU, förgasning, metanol, cirkulära kemikalier

Förord

Kol- och klimateffektiv användning av biogent avfall för cirkulära kemikalier projektet är ett forskningsprojekt finansierat inom ramen för Bio+ programmet hos Energimyndigheten. Projektet pågår från januari 2023 till mars 2025. Vi vill tacka alla på referensgruppen (Oleg Pajalic, Nader, Sudhanshu Pawar, Nader Padban, Kristoffer Pettersson, Thomas Stenhede) för deras värdefulla återkoppling på projektet.

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Sammanfattning

I takt med att industrin strävar efter att nå klimatneutralitet ökar efterfrågan på hållbara källor till biogent kol, särskilt för användning i kolbaserade material som plast. Tillgången på sådana råvaror är dock begränsad. Kommunalt avfall (MSW), som i dagsläget används för energiåtervinning i Sverige, utgör en betydande lokal källa till biogent kol. Denna studie utvärderar potentialen i att omdirigera MSW från avfallsförbränningsanläggningar till metanolproduktion genom olika teknikkonfigurationer, inklusive förgasning och koldioxidavskiljning och -användning (CCU). Livscykelanalysen visar att alla konfigurationer kan minska växthusgasutsläppen avsevärt jämfört med energiåtervinning utan CCS eller metanolproduktion. Resultaten varierar dock beroende på vilket policyramverk som tillämpas (ISO vs. RED), särskilt för CCU. Projektet undersöker även de ekonomiska och politiska konsekvenserna, och lyfter fram att RED kan ge prisfördelar för metanol som klassificeras som RFNBO, men att långsiktig hållbarhet beror på hur regelverken utvecklas. Även om metanolproduktion baserad på MSW inte helt kan möta det framtida nationella behovet, kan den avsevärt minska beroendet av fossila importvaror och bidra till en cirkulär kolbaserad ekonomi.

Summary

As industries strive to meet climate neutrality targets, the demand for sustainable sources of biogenic carbon is rising, particularly for use in carbon-based materials such as plastics. However, the availability of such feedstocks is limited. Municipal solid waste (MSW), currently utilized in Sweden for energy recovery, serves as a significant local source of biogenic carbon. This study evaluates the potential of redirecting MSW from Waste-to-Energy (WtE) plants toward methanol production through various technology configurations, including gasification and carbon capture and utilization (CCU). Life cycle assessment reveals that all configurations can significantly reduce greenhouse gas emissions compared to the Waste-to-Energy configuration with no CCS or methanol production. However, outcomes vary depending on the policy framework applied (ISO vs. RED), especially for CCU. The project also explores the economic and policy implications, highlighting that while RED could offer price premiums for RFNBO-classified methanol, long-term sustainability depends on evolving regulations. Although MSW-based methanol cannot fully meet future national demand, it could substantially reduce reliance on fossil-based imports and contribute to a circular carbon economy.

Introduction

The demand for biogenic carbon atoms is increasing as the industry attempts to comply with emission reduction goals (e.g., climate neutrality by 2045), while simultaneously meeting the rising demand for carbon-based materials, such as plastics. However, the availability of sustainable biogenic feedstock as a source for these atoms is limited. The European Commission's recently announced Clean Industrial Deal outlines a strategy that combines decarbonization, reindustrialization, and circular economy principles to enhance competitiveness and accelerate the decarbonization of EU industrial sectors, while also reducing dependency on imported feedstocks and increasing resilience amid rising geopolitical tensions. This initiative will be supported by several announced policy measures, taxation schemes, trade policies, funding opportunities, and financial instruments, creating significant near-term investment opportunities in emerging technologies that align with these strategic goals.

Waste used as fuel in energy recovery is an inherently local feedstock and a source of biogenic carbon atoms. In Sweden alone, 4.5 million tonnes of Municipal Solid Waste (MSW)[1] were generated in 2023, of which 1.7 million tonnes were collected and managed as household residual waste(Avfall Sverige, 2024). Fifty-nine percent of the total MSW collected (including household residual waste and reject fractions from material recycling) was used as fuel in the Swedish Waste-to-Energy (WtE) plants to generate heat and electricity(Avfall Sverige, 2024). Residual waste often includes materials that are unsuitable for recycling or were either unsorted or incorrectly sorted. When such waste fuel is incinerated, CO_2 is emitted, and the fossil and biogenic carbon content in the waste fuel determines the relevance of these emissions from a climate change perspective. Analysis of the residual waste from an average Swedish household reveals that it contains approximately 30% food waste and about 20% paper and cardboard. Since both are entirely biogenic, this makes household residual waste a significant source of biogenic carbon—accounting for 60% of the total carbon content in the fuel (Avfall Sverige, 2012).

Currently, Waste-to-Energy (WtE) facilities are pursuing technical solutions to meet their climate goals. One technical solution is Carbon Capture and Storage (CCS). Using a fuel with high biogenic carbon content at the WtE plants in combination with CCS could enable negative CO_2 emissions while still meeting societal demands for waste processing and

[1] The definition of Municipal Solid waste in this work is "*Waste generated by households and businesses that falls under municipal waste responsibility pursuant to Chapter 15, Sections 20 and 20a of the Swedish Environmental Code. Compared with the concept of municipal waste, construction and demolition waste from households is included, while waste from park and street maintenance is not included. Sludge and other fractions from private sewers are also included in the municipal waste responsibility, but these volumes are not included in the compilation here. However, this publication does contain a chapter on Sludge*". Source: Avfall Sverige.

heat and electricity production. However, this alternative implies the loss of valuable biogenic carbon atoms in the waste fuel that could instead be used in valuable carbon-based chemicals. This alternative could potentially support the chemical industry in reducing its reliance on fossil-based raw materials, get one step closer to a circular carbon value chain, and reduce its climate impact.

The chemical industry is currently regulated under the EU Emissions Trading System (EU ETS). In addition, the revised Renewable Energy Directive (RED III) proposes expanding its scope to include fuels used for non-energy purposes, such as feedstocks in industrial processes. This suggests that platform chemicals in the chemical industry, if produced using renewable fuels from biogenic feedstocks or carbon capture and utilization (CCU) pathways, could potentially be recognized under national RED targets for renewable energy use (Fossilfritt Sverige, 2024).

This project evaluates various technology configurations for utilizing the MSW, currently used for energy recovery to produce platform chemicals, thereby recycling both biogenic and fossil carbon atoms in the feedstock. Specifically, we evaluate if using the carbon in MSW to produce circular chemicals might be a better option compared to the WtE recovery of MSW combined with CCS from a climate-, cost-, and policy perspective. The following chapters outline the technology configurations and scenarios developed concerning the composition of waste, the policy landscape, and the price of the commodities. Considering the expected changes in municipal solid waste (MSW) composition, market dynamics, and policy developments, the technology configurations were evaluated for the current year (2024), as well as projected scenarios for 2030 and 2045.

Technology configurations

The technology configurations investigated are based on the production of platform chemicals from MSW via gasification and energy recovery coupled with carbon capture and utilization (CCU). Methanol (as a platform chemical) was assumed to be the product due to its high versatility. Five configurations were studied, including three configurations for methanol production and two reference configurations:

- Gasification followed by syngas conversion (*Gasification*)
- Hydrogen Boosted Gasification followed by syngas conversion (*Gasification-H_2*)
- Waste to Energy with Carbon Capture and Utilization (*WtE-CCU*)
- Reference Waste to Energy (*Ref-WtE*)

- Reference Waste to Energy with Carbon Capture and Storage (*Ref-WtE-CCS*)

Process simulations were conducted in Aspen Plus to evaluate the performance of each configuration at a large scale (100 MW thermal input). Each configuration was optimized to maximize methanol production and enhance heat integration within the plant, utilizing commercially available technologies where applicable. Figure 1 shows the simplified scheme of methanol production through the gasification configuration. The MSW, after pretreatment including drying, enters the gasifier where it is converted to syngas (a mixture of mainly CO, CO_2, CH_4, and H_2) by oxygen-blown steam gasification. The gasifier is a bubbling fluidized bed suitable for waste conversion due to feedstock composition, size flexibility, rapid heating, consistent operation, and lower capital costs compared to other gasifiers (Santos et al., 2023). The produced syngas is then cleaned by particle- and tar removal, followed by removal of sulfur compounds (mainly H_2S). In the *Gasification* configuration, the H_2/CO ratio in the gas is then adjusted in the water-shift reactor where part of the CO in the syngas reacts with steam and produces CO_2 and H_2. In the *Gasification-H_2* configuration, H_2 produced by water electrolysis is added to the syngas to adjust the H_2/CO. in both configurations, the H_2 and CO_2 mixture is then fed into the methanol synthesis reactor, where it undergoes catalytic conversion into methanol at 65 bar and 250°C. The resulting methanol is subsequently purified by distillation.

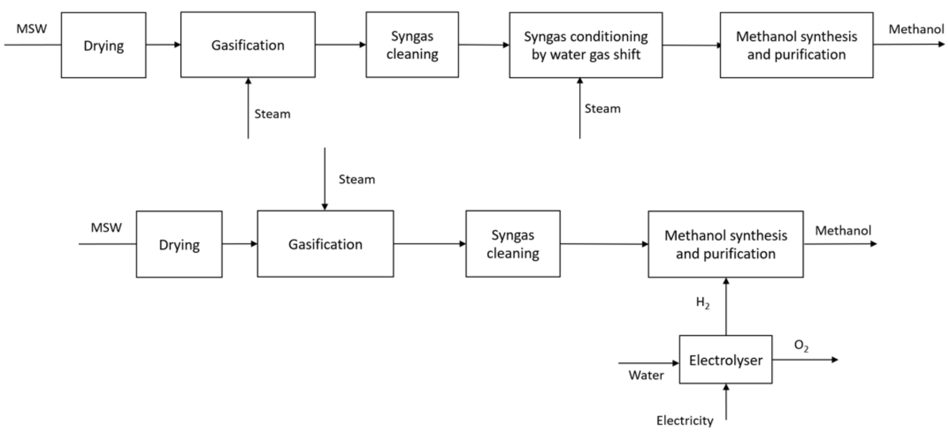

Figure 1. Schematic of methanol production by Gasification and Gasification-H_2 followed by methanol synthesis and purification

Figure 2 schematically shows methanol production through hydrogenation of the captured CO_2 from the WtE plant. The hydrogen required for the hydrogenation process is generated through water electrolysis. CO_2 is captured from the flue gases by the monoethanolamine (MEA) solvent. H_2

and CO_2 are then compressed before being mixed and contacted with the catalyst in the methanol synthesis reactor.

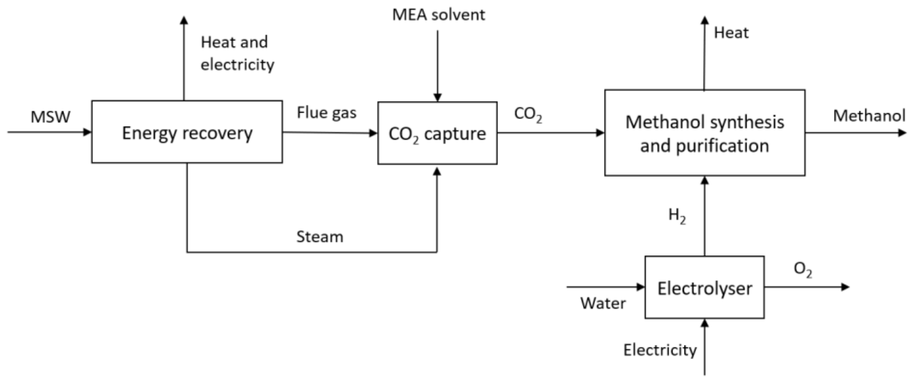

Figure 2. Schematic of methanol production by hydrogenation of the captured CO_2 from the waste-to-energy plant

Scenarios for MSW composition

The composition and the amount of MSW used as feedstock in thermal treatments are influenced by regional aspects (i.e. seasonal variation, weather, location, waste collection and processing technology available); economic factors; social aspects (i.e. consumption and behavior patterns), technologies available as well as policy instruments related to waste management, circular transformation, and resource management. Changes in waste composition can impact both the quality of the feedstock and the quality of the products derived from its processing.

Two future scenarios (2030 and 2045) have been developed to reflect the effect of potential interventions such as policy incentives or behavioural changes in the amount and composition of the Swedish residual household waste currently used in energy recovery. The average composition of Swedish residual household waste in 2023 was selected as the current/reference scenario. The average composition is based on the predictions made by Bisaillon et al. (2013), which were based on fuel and chemical analyses of Swedish waste used in energy recovery. The future scenarios (2030 and 2045) have been developed considering past experiences, current trends in the sector, effects of current and upcoming policy instruments, and discussions with experts in the field. The assumptions are as follows:

- The household residual waste was divided into four different waste fractions: food waste, plastic and paper/cardboard packaging, and *other combustibles*. The last fraction refers to all the combustible materials in the household residual waste that are not included in the fractions previously mentioned, for example, diapers. The estimated changes in the waste fractions presented below are based on personal discussions with experts in the field and consider current trends.

- Since the 1st of January 2025, it is mandatory for households and companies in Sweden to source and sort food waste (Naturvårdsverket, 2023). Thus, the amount of food waste in residual household waste is assumed to be reduced by
    - 10 wt.% between 2023 and 2030.
    - 30 wt. % between 2030 and 2050.
- The amount of plastic packaging in the Swedish household residual waste is expected to decrease due to the introduction of curbside collection(Naturvårdsverket, 2023) since the 1st of January 2024 - and that must be fully implemented by the 1st of January 2027 - by
    - 31 wt. % by 2030(Granberg, 2024).
    - 50 wt.% by 2050.
- The amount of paper and cardboard packaging in the household residual waste will be reduced due to the introduction of curbside collection since the 1st of January 2024– and that must be fully implemented by the 1st of January 2027 - by
    - 10 wt. % by 2030.
    - 65 wt.% by 2050.
- The among of biogenic plastics in the household residual waste is expected to increase over the years what will impact the biogenic/fossil carbon share in the Swedish household residual waste leading to
    - 5 wt.% biogenic C vs 95 wt.% fossil C by 2030.
    - 20 wt.% biogenic C vs 80 wt.% fossil C by 2050.

Limitation of the waste composition scenarios developed in this work is that the scenarios presented refer to households and businesses that fall under municipal waste responsibility. External factors to waste management, such as energy demand, have not been considered. Based on the scenarios developed, the ultimate and proximate analysis of MSW is estimated and used in the process models to evaluate the carbon efficiencies of the technology configurations.

Life cycle assessment methodology

To assess the climate impact of the studied technology configurations, Life Cycle Assessment (LCA) was performed comparing the methanol production pathways to two WtE reference cases for three time periods: current (2023), 2030, and 2045. The main assessment is based on the ISO 14040-44 methodology, and a comparison is made with the methodology set out in the Renewable Energy Directive (RED). The main assessment follows a consequential approach, analysing the effect of redirecting the CO_2 (in the CCU case) or waste (in the gasification cases) from the existing WtE plant to produce methanol. The compared cases and methodology details, such as assumptions and data, are further described below.

Description of assessed cases

Error! Reference source not found. gives a simplified overview of the studied technology configurations, see Section 2.2 for more details. The common denominators across all cases are:

1) The same amount of energy input by waste (100 MW) is processed.

2) Methanol is produced

The functional unit is defined as 1 MJ of methanol, reflecting the primary purpose of the studied technology configurations. To enable comparison with reference cases that do not produce methanol, these cases include conventional fossil-based methanol production and use. The quantity of fossil methanol per unit of treated waste is assumed to match that of the WtE-CCU configuration, which has the highest methanol yield. This assumption provides a conservative estimate of the reference cases' impact. The environmental impact of fossil methanol is based on the emission factor specified in the Renewable Energy Directive (RED) (97.1 g CO2e/MJ)[2].

[2] Delegated act to RED

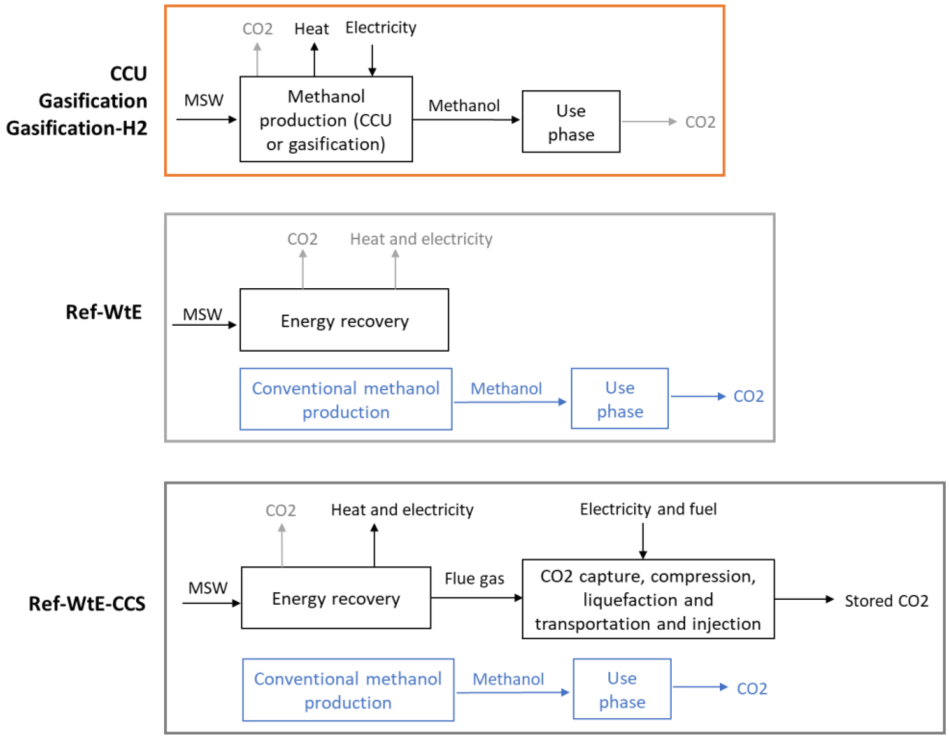

Figure 3. Schematic overview of the studied cases compared in the climate assessment.

It is assumed that methanol is combusted at the end of life in all cases (i.e., not stored in a product with a long lifetime), releasing the carbon into the atmosphere, except for the CCS case, where most of the CO_2 is stored. As previously mentioned, the LCA follows a consequential approach, meaning that the impact of redirecting CO_2 or waste for methanol (or CCS), compared to incinerating waste for heat and power, as in the reference WtE case, is evaluated. Consequently, CO_2 emissions from the waste are considered zero in all scenarios (except for the CCS case), as there is no net change in emissions compared to the reference case. These CO_2 flows are therefore highlighted in grey in Figure 3. The same principle applies to the electricity and heat generated by the reference WtE plant—only deviations in output are accounted for in the CCU, gasification, and CCS scenarios.

ISO vs RED methodology

The ISO and RED methodologies were compared in this study. While the ISO standard offers a general framework for conducting life cycle assessments (LCAs), the Renewable Energy Directive (RED) provides a more specific methodology tailored to different fuel types. Although RED currently focuses on greenhouse gas (GHG) quantification for fuels, its relevance extends to this project because methanol, although used here as a chemical, is explicitly addressed within the RED framework at the EU level. In addition, RED may in the future include non-energy uses of fuels, such as those in the chemical industry. Therefore, it is reasonable to assume that the same rules and criteria could apply to methanol when used as a platform chemical. RED applies distinct calculation rules depending on the type of fuel and its feedstock. As a result, even if the end product is the same, the applicable rules under RED can vary significantly based on the production pathway.

Depending on the LCA methodology applied, different portions of the produced methanol may be classified as biofuels, recycled carbon fuels (RCFs), or renewable fuels of non-biological origin (RFNBOs).

The key methodological distinction between ISO and RED for this project relates to how impacts from electricity are considered. In ISO, the impact from resources should apply a life cycle perspective and include indirect emissions. For example, for electricity, this implies the inclusion of indirect emissions from renewable electricity production. In RED, fully renewable electricity should not be burdened with any emissions, i.e., no indirect emissions are included. For RFNBOs, grid electricity could be classified as fully renewable in all parts of Sweden (given a Power Purchase Agreement in the bidding zones SE3 and SE4). For biofuels, a country specific emission factor should be applied. For RCF, a country or bidding zone specific emission factor should be applied. Grid electricity could only be classified as fully renewable for RCF if the fuel is produced during hours of excess renewable electricity. In this study, a country-specific emission factor for Sweden is assumed for the RCF production.

The RED methodology is specific in its rules for assessing climate impact. However, these rules are not always clear or easy to interpret. The calculations according to RED represent one interpretation of the rules. Ambiguities, inconsistencies, and other uncertainties regarding the assessment method in RED are further discussed in the project “Klassificering och hållbarhetskriterier för förnybara drivmedel i EU - vad gäller egentligen?”(Bio+ portalen, 2025). One important uncertainty is what methodology to apply when the fuel is a mixture of biofuel and RCF and should have the same emission intensity, which becomes an issue in gasification cases. In this project, the calculation rules for RCF were applied to those cases, as this is believed to be the most correct interpretation.

Data collection and assumptions
Inventory data for the three technology configurations were derived from mass and energy balances resulting from the process modelling. Data for the reference plants were however, mainly extracted from literature. Emission factors to quantify the climate impact were principally collected from the Ecoinvent 3.9 database and RED.

For future scenarios, the emission factors were decreased for most types of resource use. For the ISO calculations, the most significant change pertains to the Swedish electricity mix, where the emission intensity is assumed to decrease by 20% by 2030 and 50% by 2045. For transport, emission reductions over time were expected to align with the EU's climate targets and the specific targets outlined for transport in RED and FuelEU Maritime. Some emission factors were not anticipated to change over time; these include, for example, the fossil reference methanol. The RED methodology only provides descriptions of how calculations should be made under current conditions. For this study, the RED-specific emission factors, for instance, electricity, were therefore assumed to remain constant over time. Other emission factors, such as those for transport and sorbents, were expected to decrease over time in accordance with the ISO calculations.

Policy scenarios

This study surveyed existing and proposed EU directives to understand the future policy landscape for the valorisation of MSW into platform chemicals. Various existing markets for biofuels were also analyzed to conclude potential future developments and their implications for the economic viability of proposed technology configurations.

Currently, the chemical industry lacks significant market and policy incentives for adopting renewable feedstocks. However, as the industry is subject to the EU-ETS, the phasing out of free emission certificates from 2027 (European Commission, 2021) will likely increase demand for renewable feedstocks, such as renewable methanol. These feedstocks will likely fetch a price premium over their fossil counterparts, which is dependent on their specific climate performance.

The assessment of climate impact for feedstocks, such as methanol, in the chemical industry can vary based on policy implementation. This work examines the impact of these variations by comparing climate impact assessments under ISO and RED standards.

Beyond the differences in assessment protocols, the implementation of the RED in road transport has allowed for double counting of fuels that meet specific criteria and establishes sub-targets for advanced biofuels and RFNBOs. These sub-targets aim to foster niche markets, potentially resulting in distinct pricing structures for these fuel categories compared to other biofuels. These types of sub-mandates and niche markets could potentially be transposed to the chemical industry if it becomes subject to the RED.

The current policy landscape presents two contrasting future scenarios that could significantly impact technology configurations for converting MWS into platform chemicals, which we here refer to as: (i) EU-ETS-Scenario and (ii) RED-Scenario.

In the **(i) EU-ETS-Scenario**, the price premium of the produced methanol compared to its fossil equivalent is directly related to its GHG performance and the assumed CO_2 prices. No additional income is expected from different classifications of the produced fuel fractions. Here, the ISO methodology is used to assess the GHG performance of the technology configurations.

In the **(ii) RED-Scenario**, the GHG performance of the produced methanol is assessed according to the RED guidelines. Depending on market and policy developments, different price premiums can be assumed for the various produced methanol fractions, with a potential for double counting (RED-DC).

- **Bio-Methanol:** Methanol produced from the biogenic fraction of MSW can be valued similarly to advanced biofuels in the transport sector, potentially qualifying for double counting. However, if chemical industry legislation aligns with aviation and maritime sectors, which exclude non-Annex IX feedstocks, the price premium would likely only reflect the fossil fuel price and GHG performance of the methanol. Thus, we assume this fraction will not be eligible for double counting under any policy framework.

- **Renewable fuels of non-biological origin (RFNBO):** The produced methanol fractions classified as RFNBO could have their price directly tied to the CO_2 price and its GHG performance, this is likely under a future scenario where either 1) no introduction of specific sub-quotas for use of RFNBO in the chemical industry, or 2) rapid commercialisation of other technologies to produce RFNBOs resulting in a downward price pressure making them cost-competitive with their biofuel counterparts. In other policy scenarios where additional policy support specifically targeting RFNBOs in the chemical industry is provided, such as double counting, the price potentially doubling its price premium based on CO_2 emissions and GHG performance.

- **Recycled carbon fuels (RCF):** The methanol produced from the fossil fractions in the MSW, classified as RCF, is expected to have the same price premium as advanced biofuels up to 2040, reflected by its GHG performance. However, after 2040, the price is anticipated to align with fossil methanol.

Price scenarios

The price scenarios were derived from a combination of historical price data and future price scenarios, depending on availability. The prices are categorized into low, mid, and high price points. For CO_2 and electricity, specific prices are listed for years 2024, 2030, and 2045, where 2023 prices are based on market prices for the last 5 years. The specific prices do not indicate likelihood but represent a broad range of potential prices. This approach allows for a comprehensive evaluation of the techno-economic performance of the technology configurations under various future market developments. Table 1 presents the different prices used for each specific commodity and year.

Table 1. Commodity prices. The monetary values have been adjusted to EUR 2023 using historic European Central Bank (ECB) exchange rates Harmonized Index of Consumer Prices (HCIP).

Commodity	Year	Low	Mid	High	Price unit	Sources	Notes
MSW	All years	70	87	174	EUR/ton	Assumption	
Electricity	2024	20	40	60	EUR/MWh	(ENTSO-E, 2024)	
	2030	41	46	64	EUR/MWh	(SVK, 2024)	
	2045	38	46	68	EUR/MWh	(SVK, 2024)	
(Fossil) Methanol	All years	206	330	500	EUR/ton	(Methanol Institute, 2024)	Historic high, low and average prices in Rotterdam 2021-2023
CO_2	2024	20	51	89	EUR/ton	(World Bank, 2024)	Low, average, and high (annual)CO2 prices for the period 2019-2024
	2030	34	125	129	EUR/ton	(European Commission et al., 2021; Swedish Energy Agency, 2023; IEA, 2024)	
	2045	146	172	231	EUR/ton	(European Commission et al., 2021; IEA, 2024)	

O_2	All years	0	40	88	EUR/ton	Assumption
District heat	All years	15		35	EUR/MWh	Assumption

Technical and environmental performance of the technology confiugrations

Figure 4 shows the amount of carbon in the methanol produced in each case and demonstrates how the carbon efficiency for the different configurations changes with the composition of the MSW. As seen, the gasification case shows a decrease in efficiency while the CCU and gasification-H_2 cases are unaffected.

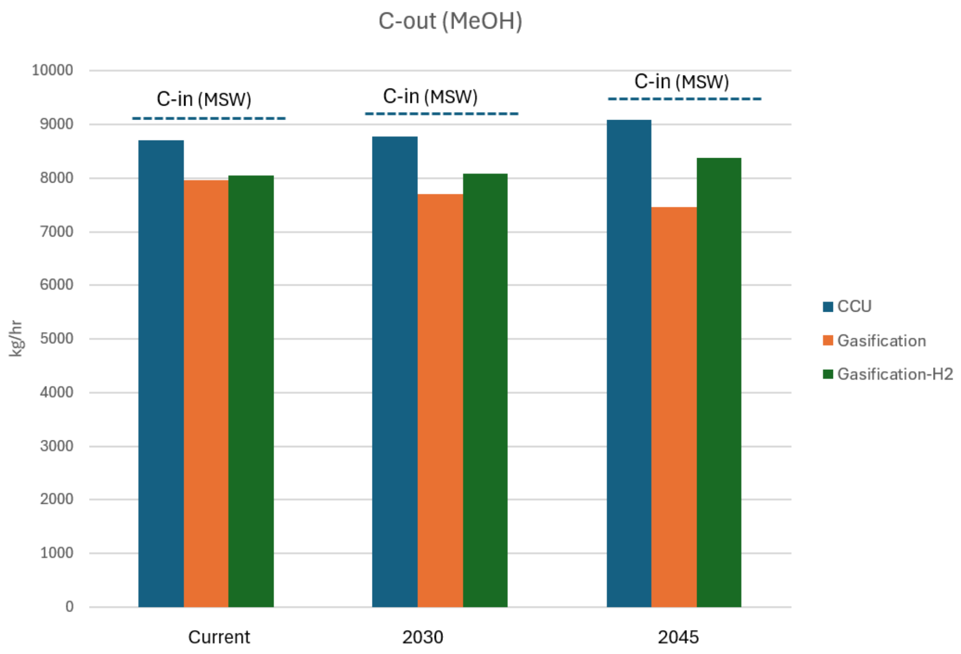

Figure 4. The amount of carbon in and out of each configuration under the current, 2030, and 2045 scenarios

Environmental assessment results

This section outlines a summary of the environmental assessment results. The climate impact results for 2023, according to ISO and RED are shown in **Error! Reference source not found.**. Methanol production for all studied technology configurations results in a large climate impact reduction compared to the reference WtE case. Comparing the results according to ISO, the CCU case has twice as large an impact as the gasification cases. There is no significant difference between gasification with and without hydrogen in terms of climate impact. This is because the hydrogen usage is relatively small for the gasification H_2 configuration (0.1 MJ H_2 per MJ methanol compared to 1.2 MJ H_2 per MJ methanol for the CCU configuration).

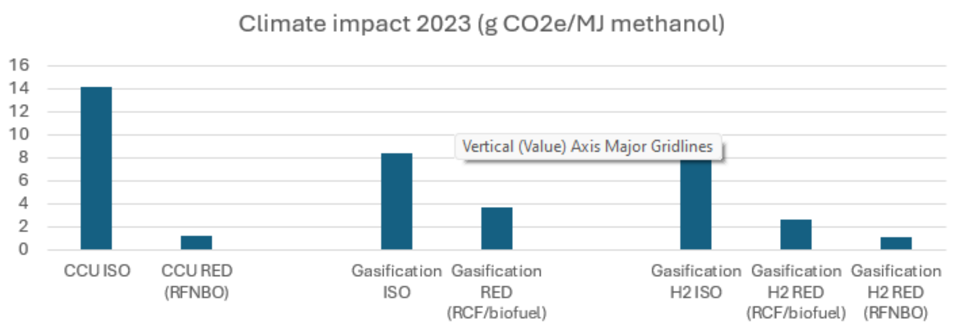

Figure 5. Climate impact for the studied technology configurations for the current scenario according to ISO and RED, as well as the reference cases.

There are significant differences between the ISO and RED results, especially across different cases. For the gasification-H_2 configuration, two separate values are considered for RED: one for the biofuel and RCF share, and another for the RFNBO share. According to RED, the biofuel and RCF should have the same emission intensity, while the RFNBO must be calculated separately. The main reason for the differences between ISO and RED results is the emission factor for electricity. Although all scenarios assume an average grid electricity mix, the emission factors differ:

- ISO (2023): 9.0 g CO_2e/MJ
- RED for biofuel and RCF: 4.1 g CO_2e/MJ
- RED for RFNBO: 0 g CO_2e/MJ

This variation has a major impact, especially in electricity-intensive configurations like CCU. Since RFNBOs are assigned a zero-emission factor for electricity, their climate impact is very low, less than 2 g CO_2e/MJ, mostly due to fuel distribution.

Over time, the climate impact remains constant for the reference (WtE) configuration. However, for other cases, climate impact decrease due to the assumption that electricity will have a lower impact in the future. Under RED, this time-based reduction is generally not significant, since emissions are already low, except for the RFNBO from the CCU configuration.

According to RED, fossil CO_2 from CHP plants cannot be accounted for as burden free after 2041[3]. At 2045, the methanol from the CCU configuration therefore no longer meets RED's sustainability criteria. The way the rules are formulated now, the fossil carbon used to produce the RCF appears to remain burden free after 2041. The RFNBO from the gasification H_2 configuration continues to have a low climate impact 2045 since it only covers the hydrogen, and all carbon from the waste is allocated to the biofuel and RCF.

Other environmental impact categories

Assuming Sweden and the EU meet their net-zero climate targets by 2045 and 2050, respectively, all the methanol production pathways studied are expected to have a low climate impact in the future, as our results suggest. However, despite their low emissions (based on ISO calculations), these pathways are resource-intensive and may lead to other environmental impacts unrelated to climate change.

Water is one of the key resources used in methanol production. All the configurations described in this report involve water-intensive processes, such as the water-gas shift reaction in gasification and electrolysis for hydrogen production. Additionally, all configurations require substantial amounts of cooling water. The carbon capture process is particularly water demanding. According to the IPCC, water use in facilities with CCS can be 25–200% higher than in those without CCS, mainly due to the extra energy required and the associated cooling needs (Clarke, 2022).

Water is a resource that is likely to become more limited in the future due to changes in available water and increased water use. In Sweden, the available water is expected to increase over time(Sjöstrand et al., 2019). However, when looking at seasonal and regional patterns, water availability is expected to increase during autumn and winter in most areas but decrease during summer across nearly all regions. This seasonal imbalance suggests that deploying water-intensive technologies—such as CCS or electrolysis—could contribute to water scarcity, even in a country like Sweden. The

[3] Point 10, Annex 10, the delegated act on RFNBO and RCF. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1185

impact would depend on the time of year, the specific region, and the presence of other water-demanding activities in the area.

Electricity is another critical resource in methanol production, particularly in the CCS configuration, which relies heavily on electricity to power electrolysers for hydrogen production. While Sweden's electricity supply is largely renewable, it remains a limited resource with growing demand from other sectors, such as industry and transportation, as they undergo electrification. Moreover, electricity generation—regardless of the source—can have a range of environmental impacts beyond climate change. These include effects on biodiversity, land use, and the extraction of critical raw materials needed for infrastructure and technology.

Policy analysis

The impact of the policy frameworks mentioned above, frameworks on income from methanol production, considering different technology configurations and current methanol and CO_2 prices (330 EUR/MWh and 51 EUR/ton, respectively), including a sensitivity analysis for high and low CO_2 prices (20 and 89 EUR/ton), as well as varying shares of methanol classified under different fractions, is illustrated in Figure 6.

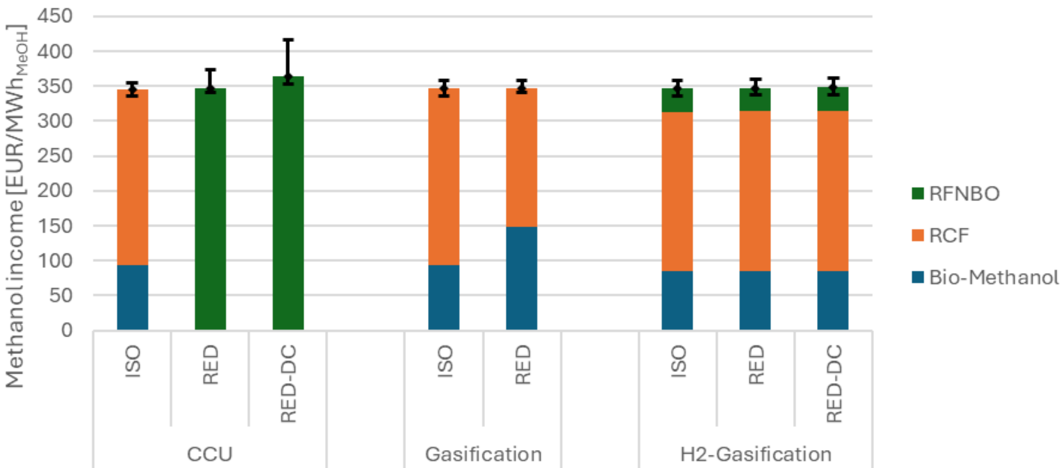

Figure 6. Methanol income by technology configuration under various GHG accounting frameworks (ISO, RED, RED-DC), segmented into RFNBO, RCF, and Bio-Methanol contributions, based on current methanol and CO_2 emission prices. DC=Double Counting. Since only RFNBO is assumed to be subject to double counting of the GHG emission reduction potential under the RED-DC policy scenario, the Gasification technology configuration has no difference under the RED, and RED-DC policy frameworks.

Methanol demand and impacts of large-scale implementation of technology configurations

Building on the findings from the other work packages, the energy systems analysis offers an overview of the potential for large-scale methanol production from municipal solid waste (MSW) in Sweden, in relation to overall feedstock demand. It also assesses the climate impact of such an implementation in the context of national climate targets.

The calculated potential of methanol production from MSW in Sweden is, at present, between 600 000 and 700 000 ton/annually, depending on technology configuration (Figure 7). This potential is expected to decrease over the next decades to between 300 000 and 400 000 ton/annually, mainly due to the reduced amount of available MSW.

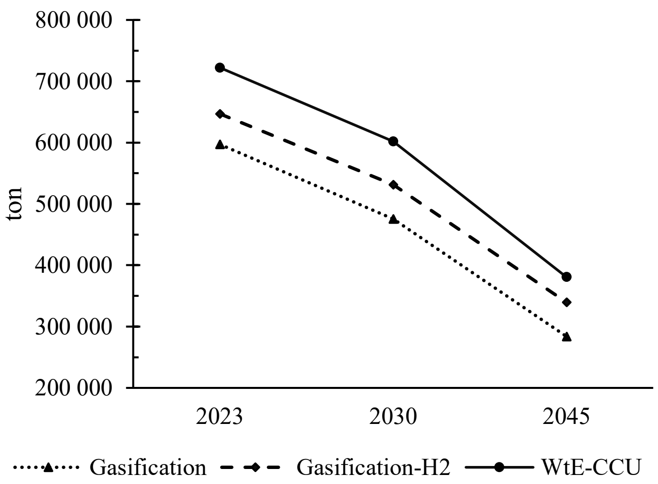

Figure 7. Total potential methanol production from municipal solid waste for the different pathway technologies

If the methanol demand of the Swedish chemical industry follows the global scenario by IEA (2013), it is expected to increase from 200 000 ton/year in 2020 to between 420 000 and 510 000 ton/year in 2050. This assumes that Swedish industry stays at their current competitiveness level on the international market and is increasing its production of goods that use methanol as a feedstock at the same pace as its international peers. Another potential scenario, is a “frozen” business as usual, meaning that the chemical industry does not increase or decrease its current demand for methanol of about 200 000 ton/year. Relating the potential methanol demand in Swedish chemical industry in the coming decades to the total potential methanol production from MSW for the different technology pathway show that, given the estimated trends, the methanol demand and methanol production will intersect before 2045. Thus, even if all the

Swedish households' solid waste were used for methanol production, there would still be a need to cover the demand in other ways, e.g., use of other feedstock than MSW for methanol production, import of MSW, production of e-methanol, or other conventional methanol production.

Bio-methanol can also be used to replace other fossil-based platform chemicals. For example, in the production of propylene and ethylene — two high-volume chemicals produced in Sweden — the feedstock can be replaced with bio-methanol. However, the potential for using methanol as feedstock in propylene and ethylene production is vastly larger than the potential for methanol production from MSW (A difference of about 1.8 million tonnes). Even if the production volumes stay at the current level, there would still be a significant gap between national production of methanol from MSW and ethylene/propylene production capacity.

Using the calculated carbon footprint of the technologies studied for methanol production, and assuming full implementation of methanol production from MSW, the climate impact from the production has been estimated.

In contributing to reaching the Swedish climate goals, conventional methanol produced from natural gas has a carbon footprint of up to 97.1 g CO_2-eq/MJ[4] (Methanol Institute, 2022), which would correspond to about 550 000 tonne CO_2 per year at 2045, given the same amount of methanol production as gasification of MSW could provide. This implies that, potentially, by replacing conventional production of fossil fuel-based methanol with renewable methanol from MSW, by 2045 the climate impact from methanol demand could be reduced by up to 520 000 CO_2 per year in 2045. Given the full implementation of MSW valorisation to methanol by 2030, the total amount of CO_2 between 2030 and 2045 would be roughly between 16.7 and 17,6 million tonne avoided CO_2 (not considering the WtE-CCU configuration).

Discussion and conclusions

The results from the life cycle assessment in this project show that all technology configurations have the potential for large GHG emission reductions compared to the reference WtE case. However, the gasification configurations have a lower impact than the CCU configuration when calculating according to ISO. Over time, this difference is evened out, given that the climate impact from electricity will reduce. The results also reveal that the choice of methodology has a significant impact on the outcomes,

[4] Calculated following the European Renewable Energy Directive (RED II).

even when analysing the same dataset. For the gasification configurations the differences in results are minimal between ISO and RED as well as over time. For CCU, the results differ greatly between ISO and RED, and for the current and the 2045 scenarios. It is, however, still unclear if and how methanol for non-energy uses will be implemented into RED.

According to RED the CCU case has the lowest climate impact today but the highest for 2045 of the studied configurations. The rules for using fossil carbon after 2041 differ for RFNBO and RCF, despite using the same waste feedstock. This incentivizes gasification over CCU over time. However, it is unclear if the rules for RCF will change and the fossil carbon for RCF also will be burdened in the same way as for RFNBO.

Depending on which future policy framework the chemical industry will fall under, the different technology configurations are expected to be able to fetch different price premiums for the produced methanol. However, the impact from changing policy frameworks is relatively small compared to the impacts from changes in CO_2 prices. Notably, the WtE-CCU technology configuration has the potential for significant economic benefits under RED policy framework, as it can produce methanol classified as 100% RFNBO. Under RED, there exists specific sub-mandates for RFNBOs which will result in niche markets that could fetch a considerable price premium compared to other renewable methanol sources.

MSW-based methanol production cannot fully cover the methanol demand of the Swedish chemical industry in 2045 unless a frozen demand (based on 2020) for methanol is assumed, or the demand is at least partly covered with e.g., other technologies for renewable methanol. Bio-based methanol has the potential to reduce the climate impact with up to 520 000 ton CO_2-eq./annually in 2045 if it replaces fossil-based methanol imports, assuming a full implementation of the studied technology pathways.

List of publications

1. Carbon and climate-efficient use of household waste for circular chemicals in Sweden (Manuscript)

2. Transforming Waste into Value: Sustainable Production of Platform Chemicals in Sweden, Venice Waste Symposium, Nov 2024

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Bilagor

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