An Assessment of the Global Warming Potential of Municipal Solid Waste Treatment Scenarios in the Netherlands

Sustainable Development Master’s Thesis

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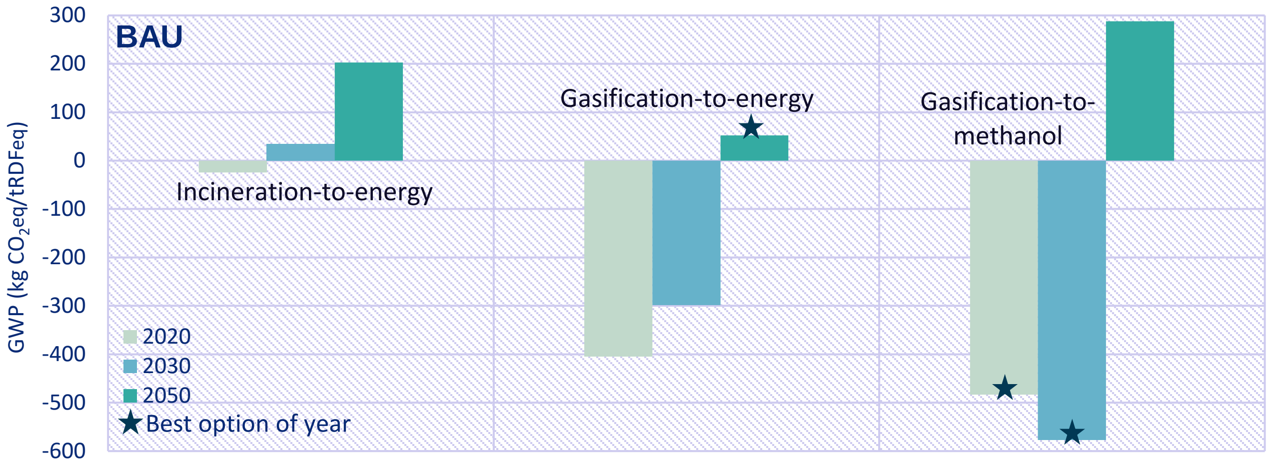
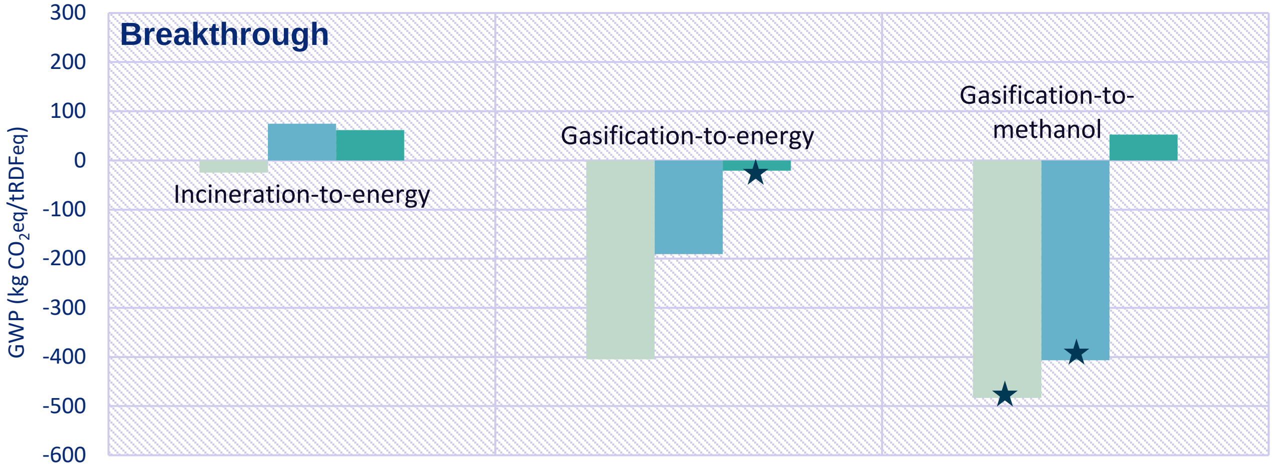
Executive Summary

Each year, 1.3 billion tons of municipal solid waste (MSW) is generated globally, and this figure is expected to nearly double to 2.2 billion tons by 2025. If this waste is not sustainably treated, it can lead to several harmful environmental impacts including soil pollution, air pollution, and climate change. The Netherlands, however, is one of the several countries beginning to shift their mindset from perceiving waste as a harmful by-product to rather a valuable resource to be used for energy, materials, chemicals, and other sectors. Currently, 97% of non-recyclable MSW is incinerated for energy recovery in the Netherlands. Yet, there are other alternatives that are potentially more sustainable, such as gasification, which is becoming increasingly relevant to the Netherlands since the announcement of the construction of a waste gasification-to-methanol plant to be built and operational by 2020 in the Port of Rotterdam. This research thus studied the global warming potential (GWP) of this waste gasification-to-methanol technology, gasification-to-energy, and the conventional incineration-to-energy in the Netherlands in 2020, 2030, and 2050 to deduce which would be optimal in terms of climate change mitigation. A comparative attributional life cycle assessment (LCA) is performed to quantify the GWP of each waste treatment and compare it to that of the reference energy or methanol it would likely replace in the market. For 2030 and 2050, two scenarios are developed, a Business-as-Usual (BAU) which serves to represent a future in which developments in renewable energy, renewable methanol, and biobased materials develop as currently expected and the Breakthrough Scenario (BT), which demonstrates a future in which large advancements are made in these areas.

The LCA results show that the largest contributor to emissions for all waste treatments is direct emissions from the combustion of waste or syngas, and to a lesser extent the necessary auxiliary energy, flue gas cleaning, and other processes. As shown in the figure below, in 2020, gasification-to-methanol is observed to be the optimal waste treatment as it leads to a net reduction in GWP of 484 kgCO2eq, or 48%, when compared to the reference methanol. In 2030, gasification-to-methanol remains as the optimal waste treatment in both scenarios, with a net GWP reduction of 577 and 470 kgCO_2eq/t RDFeq in the BAU and BT Scenarios respectively. The larger net reduction in the BAU scenario is largely due to the reference methanol being produced from natural gas whereas in the BT Scenario, 20% of the methanol is assumed to be biobased. Incineration in both 2030 scenarios leads to a net increase in GWP, implying that incinerating MSW produces greyer energy and methanol than that already provided in the market. The results for the 2050 BAU Scenario similarly show that all three waste treatments lead to a net increase in GWP. In the BT Scenario however, gasification-to-energy is still viable from a greenhouse gas (GHG) perspective as it leads to small net reduction in GWP of 11% when compared to the reference energy. The reason that waste gasification-to-methanol in this scenario leads to a net increase in GWP is partially due to the low GHG intensity of the reference methanol, which is assumed to be renewable methanol made from renewable hydrogen and waste CO_2. Though it is to a larger extent due to the lower GWP of gasification-to-methanol in this scenario. The BT Scenario assumes that the biogenic fraction of the RDF has increased to 89% in 2050 due to the replacement of biomaterials for fossil-based ones, and results in lower emissions than the BAU Scenario. The assumed biogenic fraction and lower heating value of the RDF are shown to be more sensitive to the GWP results than the carbon content of the RDF. The choice of the reference methanol and reference energy also have a large influence on the net GWP and are subjectively chosen based on the scenario.





Although the results of this study suggest that gasification-to-methanol results in the lowest net GWP when compared to the reference in 2020 and 2030, waste management decisions depend on many factors other than GHG emissions. Since the Netherlands has already heavily invested in waste incineration infrastructure, it is likely that these plants will continue to operate until their end of life. After this however, of the options studied, it is advisable to build gasification plants rather than rebuild new incineration plants from a climate change perspective. Yet, it was shown that even gasification will not be viable from a GHG perspective by 2050 if policy and the energy, biobased material, and chemical sectors develop business-as-usual. This proves that policy and research should put more focus on the levels higher in the waste hierarchy such as reduction, re-use, and recycling rather than end-of-pipe technology solutions such as the ones studied.

Nevertheless, MSW will most likely continue to be generated until true circularity can be achieved and requires immediate solutions. Gasification is again a better option than incineration because it provides the flexibility to resist technology lock-in and adaptability to adjust in a changing environment. Syngas is an extremely versatile intermediate and could be upgraded to a variety of products depending on market demands or the rate of decarbonization of alternatives. It is also compatible with a variety of feedstocks, so it allows for adaptation to declining volumes of MSW and shifting to other biomass feedstocks such as agricultural or forestry residues. The issue of sustainable treatment of MSW has no straightforward solutions but does provide the unique opportunity to simultaneously tackle problems of waste management, resource scarcity, and decarbonization of the economy.

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Abbreviations

AEB: Afval Energie Bedrijf

aLCA: attributional LCA

BAU: business-as-usual

CCU: carbon capture and utilization

cLCA: consequential LCA

DAC: direct air capture

ECN: Energy Research Institute of the Netherlands

EF: emission factor

EU: European Union

GHG: greenhouse gas

GWP: global warming potential

LCA: life cycle assessment

LCI: life cycle inventory

LHV: lower heating value

MSW: municipal solid waste

NEV: Dutch National Energy Outlook

RDF: refuse derived fuel

TRL: technology readiness level

WtE: waste-to-energy

WtM: waste-to-methanol

Abstract

Each year, 1.3 billion tons of municipal solid waste (MSW) is generated globally, and this figure is expected to nearly double to 2.2 billion tons by 2025. If this waste is not sustainably treated, it can lead to several harmful environmental impacts including soil pollution, air pollution, and climate change. The Netherlands, however, is one of the several countries beginning to shift their mindset from perceiving waste as a harmful by-product to rather a valuable resource to be used for energy, materials, chemicals, and other sectors. Currently, 97% of MSW incinerated for energy recovery in the Netherlands, yet, there are other alternatives that are potentially more sustainable, such as gasification, which is also becoming increasingly relevant to the Netherlands since the announcement of the construction of a waste gasification-to-methanol in the Port of Rotterdam. This research thus studies the global warming potential (GWP) of this waste gasification-to-methanol technology, gasification-to-energy, and the conventional incineration-to-energy in the Netherlands in 2020, 2030, and 2050 to deduce which would be optimal in terms of climate change mitigation. A comparative attributional life cycle assessment (LCA) is performed to quantify the GWP of each waste treatment and is compared to the GWP of the reference energy or methanol it would likely replace in the market.

In both of the scenarios developed, gasification-to-methanol results in the largest net GWP reduction when compared to the reference methanol in 2020 and 2030. In 2050, gasification-to-energy is the optimal treatment for both scenarios, however, in the Business-as-Usual-Scenario all treatments lead to an increase in net GWP. This implies that policy and research should instead focus on levels higher in the waste hierarchy such as reduction, re-use, and recycling if climate change mitigation is a priority. Since MSW is still expected to continue to be generated, gasification is a better choice than incineration because it provides flexibility in end products and could produce the energy, chemicals, or materials that are hardest to decarbonize in future decades. It also allows for a flexibility in feedstocks, and if MSW volumes were to decline as set by policy targets, it could adopt other forms of biomass. The issue of sustainable treatment of MSW has no straightforward solutions but does provide the unique opportunity to simultaneously tackle problems of waste management, resource scarcity, and decarbonization of the economy.

Keywords: municipal solid waste
global warming potential
waste-to-methanol
waste-to-energy
life cycle assessment
greenhouse gas emissions

1. Introduction

1.1 Problem Definition

Each year, over 1.3 billion metric tons of municipal solid waste (MSW) is generated globally, and this figure is expected to only grow in the coming years. Despite goals for waste reduction and transitioning to a more circular economy, it is estimated that it will nearly double to 2.2 billion metric tons by 2025 (World Bank, 2012). Poor management of this waste poses a potentially large threat to society as it can lead to several detrimental environmental and social impacts such as air pollution, soil pollution, and climate change (European Environment Agency, n.d.). This seemingly vast and mounting issue, however, can also serve as an opportunity to simultaneously tackle other issues of sustainability such as resource scarcity and decarbonization of the economy.

Many countries within the European Union (EU) are determined to use waste as an opportunity to transition towards a more circular and more renewable economy. Historically, waste was viewed as a burdensome by-product of human activity, both environmentally and financially. Yet with recent attention towards the circular economy, policy makers, industries, and society at large are rethinking how different waste streams of one system can become a nutrient or input for another (Ellen McArthur Foundation, 2013). MSW is no exception, and in the EU, there is a shift in mindset from seeing MSW as a burden to rather a valuable feedstock available for use in other industries. This is evident in the mere change in terminology from “waste management” to “sustainable material management” in the recent amendments to the Waste Framework Directive. This EU directive outlines the strategy for waste treatment and has the overarching mission to protect both the environment and human health by preventing and reducing the negative impacts of waste. It aims to do so by “promoting the principles of the circular economy, enhancing the use of renewable energy, increasing energy efficiency, reducing the dependence of the Union on imported resources, providing new economic opportunities and contributing to long-term competitiveness” (Council of the European Union, 2018). This demonstrates the cross-cutting nature of the circular economy, and how MSW can contribute to many of its founding principles.

Sustainable treatment of MSW has the unique ability to simultaneously tackle problems of waste management, resource scarcity, and decarbonization of the economy. It contains valuable materials that can be re-used, upcycled, or downcycled, preventing the extraction of limited and non-renewable resources. It is rich in energetic value and also consists of hydrocarbons that can be used as building blocks for upgrading to various chemicals or materials. Since it is partially biogenic, MSW has the potential to reduce GHG emissions when replacing fossil-based equivalents (Matsakas et al., 2017). The EU hopes to capitalize on this potential and solve these issues with policies such as the Waste and Landfill Directives, the Roadmap to a Resource Efficient Europe, and the Roadmap for a Low Carbon Economy to 2050. In the Waste Directive, a hierarchy is introduced which outlines the order of priority for the treatment of waste, as shown in Figure 1. Reduction and prevention sit highest in the hierarchy, followed by re-use, recycling, recovery, and with disposal such as landfilling as the option of last resort. In the past decades, the EU has worked to perform research and develop policy that pushes waste treatment up this ladder of sustainability (European Commission, 2010).

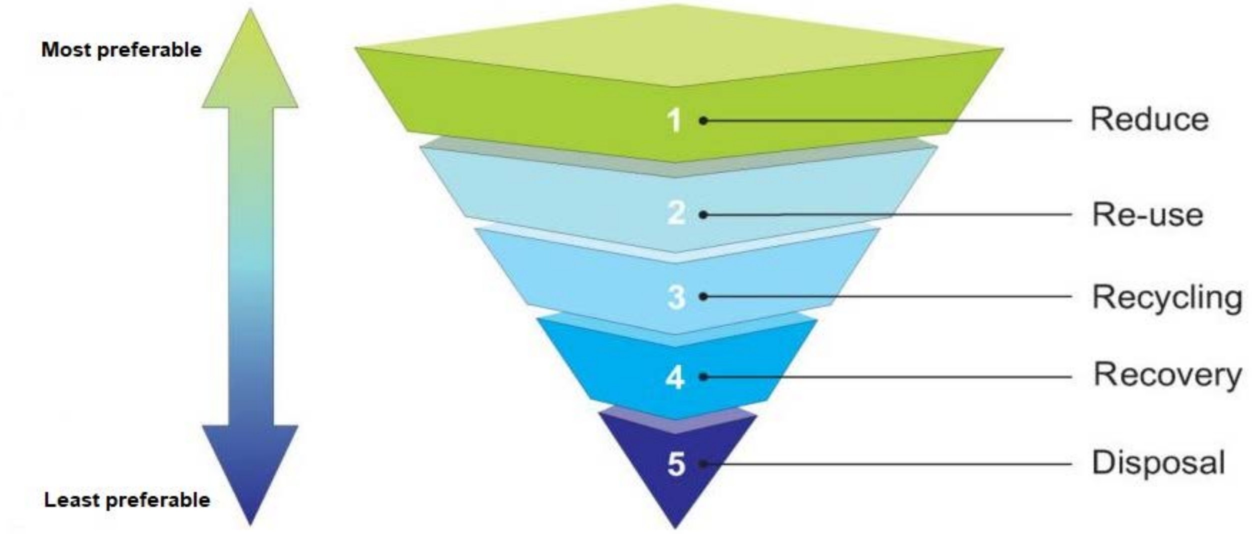


Figure 1. Hierarchy outlining the order of priority for waste treatment options.

The Roadmap to a Resource Efficient Europe has a similar ambition to keep waste as high in the hierarchy as possible by transforming it into a resource and feeding it back into the economy as a secondary raw material. It envisions waste management in which "energy recovery is limited to non-recyclable materials, landfilling is virtually eliminated, and high-quality recycling is ensured". In the Roadmap to a Low Carbon Economy in Europe, a lofty goal is made to reduce greenhouse gas (GHG) emissions by 40% in 2030 compared to 1990 levels which requires emission cuts across all sectors, including power, transport, buildings, industry, and agriculture (EC, 2011b). Sustainable waste treatment could help play a partial role in these reductions because MSW has the potential to be refined into a spectrum of value-added products ranging from energy to chemicals to materials that can replace virgin materials and fossil-based equivalents (Matsakas et al., 2017).

MSW is increasingly seen as a valuable and versatile feedstock that is abundant in energy to be harnessed, chemical building blocks to be extracted, and materials to be reused or recycled (Matsakas et al., 2017). The advantages of MSW are that it is currently available in large concentrated quantities, is relatively steadily available throughout the year, and comes at a low or even negative cost (Aracil, Haro, Giuntoli, & Ollero, 2017). In terms of scale, the amount of waste produced globally is the same order of magnitude as the sustainable potential of agricultural residues, a type of second generation feedstock that is regarded as one of the most promising for the biobased economy (Aracil et al., 2017; McKinsey&Company, 2016). Yet, unlike some agricultural residues that were not mobilized prior to incentives from biobased economy, MSW already has well established supply chains in high income countries such as those of the EU (World Energy Council, 2016). This simplifies and streamlines the logistics of collection, a challenge that many other conventional biomass feedstocks face (Rentizelas, Tolis, & Tatsiopoulos, 2009). However, despite some of its advantages, MSW is currently only 50-65% is of biogenic origin on average, with the remainder originating from fossil sources (Iacovidou, Hahladakis, Deans, Velis, & Purnell, 2018). The composition is subject to change over time, however, and the biogenic fraction is not a characteristic that is inherent to MSW. It could be highly influenced by the phasing out of fossil fuels and concurrent expansion of biobased products, such as bioplastics for example. MSW also has the added difficulty of being very heterogeneous, moist, and partially toxic in nature and these characteristics can pose challenges during the handling and processing of this feedstock (Matsakas et al., 2017).

Another shortcoming is the risk that the valorization of MSW could consequently incentivize its production. Ideally, economies should be designed in a circular fashion that minimizes waste or eliminates the concept entirely. By making MSW a commodity, however, this could decelerate the transition towards circularity. When waste is valorized and parties profit from the generation and subsequent handling of it, they rely on and are rewarded for its constant generation, and this can work against policy and targets for reducing waste. Despite goals of waste reduction, it is forecasted that OECD countries will only reach their peak waste generation in 2050 (World Energy Council, 2016). Even the EU as a leader in the circular economy has targets to increase the re-use and recycling of MSW to only 65% by 2030 (European Union, 2018). This demonstrates that MSW will likely continue to be generated in the coming decades. Until the day economies are transformed to be entirely circular in which no waste is generated, there is still a need for sustainable waste treatment solutions in the meantime.

1.2 MSW Treatment Solutions

Of the total waste generated in the EU, MSW represents only 11%, with the remainder consisting largely of mineral and solidified wastes such as construction demolition and mining tailings, as outlined in Figure 2. Despite its small share, MSW is very heterogeneous compared to other waste streams, making it inherently more complex to handle. The EU has dealt with these complexities well and has made promising advances in the past decades. Although management highly varies across EU countries, MSW is indeed being driven up the waste hierarchy through effective policies. Overall, landfilling rates have declined while recycling, composting, and incineration rates have increased. From 2005 to 2016 the rate of landfilling declined as much as 5.5% per year and recycling rates rose from 11% to 29% from 1995 to 2016. Incineration rates have also increased, and in 2016, 68 million tons of MSW were incinerated (Eurostat, 2018). Incineration reduces the volume and toxicity of MSW, uses significantly less land than landfilling, and can even recover useful energy (Joint Research Committee Science Hub, 2017). Despite these positive attributes, more advanced technologies such as gasification have gained recent interest as an alternative waste treatment technology.

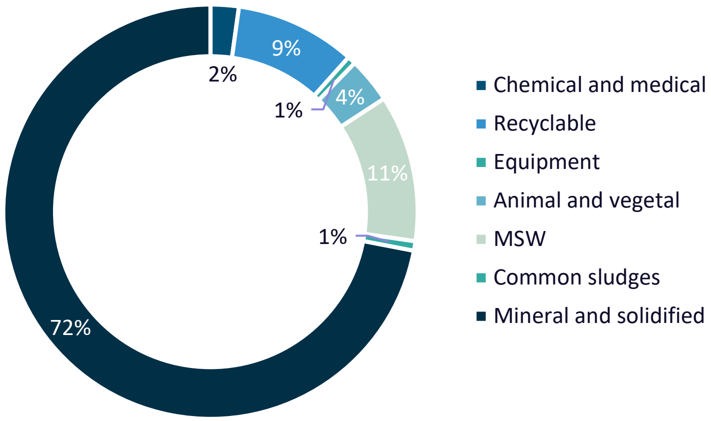


Figure 2. Waste generated in the EU in 2014 by category.

The gasification of coal and wood has existed for over a century, but this age-old technology is now exploring a new feedstock, MSW (Evangelisti et al., 2015; National Energy Technology Laboratory, n.d.-b). Gasification is defined as the high temperature chemical conversion of a carbonaceous material performed in the presence of limited oxygen. The resulting synthesis gas, or syngas, is comprised mostly of CO and H_2, and to a lesser extent CH_4, CO_2, and other impurities. Gasification of MSW is more advantageous when compared to incineration because it is cleaner, more thermally efficient, and creates a more flexible product. The reason it is cleaner than modern incinerators is because it has the advantage of cleaning syngas before it is combusted, opposed to the post-combustion cleaning of flue gases performed with incineration. Due to the oxygen deprived environment of gasification, there is also less formation of furans and dioxins and less oxidation of sulfur and nitrogen in the MSW forming harmful SO_x and NO_x emissions (Wilson, 2014). Gasification is also more thermally efficient than incineration because the clean syngas can be burned at higher temperature cycles (National Energy Technology Laboratory, n.d.-a).

In terms of product flexibility, syngas is a very versatile intermediate that can either be combusted for electricity and heat production or upgraded to high value-added products such as chemicals, fuels, or materials. These products can be synthesized by various thermochemical or biochemical pathways, with many of them of industrial interest, as shown in Table 1 (Drzyzga, Revelles, Durante-Rodríguez, Díaz, José L García, & Prieto, 2015). The technology readiness levels (TRL) of these different products highly vary, but as is apparent, syngas has a diverse range of promising applications across the transport, chemical, and energy sectors.

Table 1. Non-exhaustive list of products from syngas of industrial interest.

Chemical Catalysis	Biological Fermentation
methanol	acetate
ethanol	butyrate
dimethylether (DME)	long chain fatty acids
diesel	ethanol
naphtha	propanol
ammonia	butanol
methane	mevalonate
	hydrogen
	acetone
	2,3-butanediol (BDO)
	polyhydroxy-butyrate and -valerate
	polyhydroxyalkanoates (PHA)

There are currently 272 operating gasification plants in the world, with the majority in Asia. These plants produce power, heat, liquid and gaseous fuels, but to the largest extent, chemicals. A decade ago, only 10% of methanol and ammonia were produced via gasification but in a recent study, these figures are estimated to have risen to 30% and 25% respectively, with gasification-to-chemicals expected to continue as the most popular application in the future. Globally, the overwhelming majority of gasifiers use coal as a feedstock, and petroleum and natural gas to a much lesser degree (The Global Syngas Technologies Council, n.d.). The gasification of these fossil fuels though is very GHG intensive, and the substitution of biomass or partially biogenic MSW as a feedstock has the potential to lower the carbon footprint of these processes. Although it is technically feasible to use these feedstocks, they have not materialized to meet their fullest potential in the gasification sector. For MSW in particular, this is in part due to the challenges of handling such a heterogenous feedstock with a high moisture content and the necessity to remove contaminants that could poison downstream catalysts (Matsakas et al., 2017). Biobased feedstocks can also pose several problems with tar (large hydrocarbons) formations that condense at lower temperatures and can lead to troublesome blockage and fouling of equipment (Devi, Ptasinski, & Janssen, 2003). Yet some companies such as Canadian biofuel and biochemical company Enerkem have demonstrated firsthand that these hurdles can be overcome, and have commercialized ethanol and methanol production from MSW gasification (Iaquaniello et al., 2017). The gasification of waste presents many promising applications in the future, but it is important to first assess the sustainability of these options.

1.3 Knowledge Gap and Research Aim

As is evident, MSW is a versatile feedstock with a vast portfolio of end products that have the potential to reduce GHG emissions and mitigate climate change. As waste management advances from encompassing not only the physical disposal of waste, but to also contribute to goals of resource reduction and decarbonization, it is crucial to assess which pathways of MSW treatment can have the greatest positive impact in terms of sustainability. It is not only important to compare the impact of new emerging technologies such as gasification to conventional ones, but also to consider the different products that can be made and which products they would likely replace. Many studies have already begun to investigate these questions and compare the sustainability impacts of various waste treatment technologies. Several of them performed life cycle assessments (LCA) which can serve as a powerful tool to quantify environmental (and social) impacts for the entire life cycle of a product or process, and provide recommendations based on these results (International Reference Life Cycle Data System, 2010). Landfilling has been almost unanimously determined to be more detrimental to the environment than incineration or anaerobic digestion which justifies it placement at the absolute bottom of the waste hierarchy (Assamoi & Lawryshyn, 2012; Christensen, Simion, Tonini, & Møller, 2009). This topic has already been heavily researched; therefore, this study aims to investigate other levels of the waste hierarchy in which larger knowledge gaps remain.

A topic of more recent interest has been the comparison of gasification to other conventional treatments such as incineration (Evangelisti et al., 2015; Zaman, 2010). Zaman (2010) found that gasification is better than incineration in terms of global warming, acidification, eutrophication, and eco-toxicity and Evangelisti (2015) concluded that the observed benefits of gasification are primarily due to its higher net electrical efficiency. Most studies have focused on waste-to-energy (WtE) technologies, although there are a few more recent LCA studies that have investigated waste-to-chemicals or waste-to-fuels. Pressley et al. (2014) performed an LCA to assess the conversion of MSW to liquid transport fuels via gasification and Fischer-Tropsch from a gate-to-grave perspective and Aracil et al. (2016) similarly studied the production of biofuels from MSW compared to landfilling scenarios. Another study compared MSW derived methanol with other biobased methanol alternatives in terms of net GHG reductions, although the focus was more on the economic considerations than the environmental impacts (Iaquaniello et al., 2017). This non-exhaustive list of LCAs demonstrates that there has been some initial research investigating the environmental impacts of various MSW treatments and end products. However, there have not been many studies to date that compare *different* end products from MSW from a life cycle perspective to determine which treatment is optimal in terms of GHG reductions. Most studies also utilize secondary data from process modelling or previous LCA studies rather than using primary data from commercial plants, which is typically preferred, but often not available. Most importantly, many of these studies ignore the relation between waste treatments and their wider context; they do not consider the net effect of one technology replacing another, nor compare this to other more renewable alternatives that may be available. Lastly, the majority of the studies are snapshots of the impact of the current state of being and do not explore how these circumstances may change in the future.

This research aims to fill these gaps in the literature by performing LCAs: i) comparing different end products of MSW gasification and the respective environmental impacts ii) considering the processes and product they could replace iii) exploring scenarios for future development of both the waste technology and respective references and iv) utilizing up-to-date primary commercial data where possible. LCAs are thus performed to assess the environmental impacts of energy and methanol production from MSW. Electricity and heat are investigated as these are the most prevalent products of MSW thermal treatment in the EU (Eurostat, 2018). Methanol is also investigated to reflect the versatility of syngas and compare its use for energy versus chemical production. It is also of great interest to study because of its market size and forecasted growth. In 2016, there was a global methanol demand of over 80 Mt, and organizations such as the International Energy Agency have modeled methanol to grow over 100% in the next decade in all of their Energy Technologies Perspectives scenarios (International Energy Agency, 2016). Methanol is also specifically chosen because of a recent announcement by Enerkem, the Canadian biofuel and biochemical company who will be constructing a waste-to-methanol (WtM) plant in the Port of Rotterdam that is expected to be operational in 2020. This announcement has also narrowed the scope of the current study to the Netherlands as to more accurately reflect this local situation. LCAs can encompass a broad range of impact categories, such as eutrophication, acidification, or global warming potential (GWP) (ILCD, 2010). This research, however, only focuses on GWP, measured in mass of CO_2 equivalent, as will be later elaborated in the Methods section. Since the lifetime of an incineration or gasification plant is on the scale of 20 to 30 years, it is important to not only assess current waste treatment, but to also explore how circumstances of the wider context may change and evolve until the end-of-life of these plants (Department for Environment, Food & Rural Affairs, 2014). Investments and policies made now require foresight to remain viable in future decades. If the environmental impacts of electricity, heat, and methanol production in the Netherlands are expected to significantly change in the coming decades, the concurrent environmental net impacts of MSW treatment options may change as well. These considerations lead to the main research question:

What is the optimal pathway for MSW treatment in terms of overall greenhouse gas emissions and resulting climate change mitigation in the Netherlands in 2020, 2030, and 2050?

To answer this overarching question, a series of sub-questions are used to break it into various steps. The series of sub-questions that will help guide the central research question are:

1) *What are the GWPs associated with the incineration and gasification of 1 ton of waste to produce electricity, heat, or methanol?*
2) *How do the GWPs of these products compare to the reference products they are likely to replace?*
3) *How may the GWPs of waste technologies and their reference products change in 2030 and 2050, and how do they compare?*

The first sub-question aims to calculate the GWP of the incineration and gasification of waste for electricity, heat, and methanol production by conducting an attributional LCA. The second considers the various products and processes these could potentially replace in the market to make a comparative analysis. The third sub-question explores how these technologies and the reference products could develop and potentially decarbonize in 2030 and up to 2050. This is done by building scenarios that demonstrate different ways that the reference technologies and products could potentially develop. The results from the various decades and scenarios are then compared, and with the culmination of these findings, the main research question will be answered as to what the best use of MSW is in terms of GHG emissions in 2020 and up to 2050.

This research is relevant to sustainable development because it will help answer the overall question posed by government, researchers, and industry- *how can MSW be treated most sustainably*? MSW is a feedstock of special interest because it also intersects with the circular economy, in that waste can be utilized as an input for another product, and close energy and material loops. It also spans many different sectors, from renewable energy to materials to the chemical industry, thus it influences sustainable development in several dimensions. By examining and recommending the optimal treatment and use of MSW, this can help achieve sustainable development through waste reduction, economic growth, fossil resource reduction, and resource efficiency to ultimately mitigate climate change.

2. Theory

2.1 Life Cycle Assessments

Steps of Execution

Due to the increased concern for climate change and environmental degradation, tools have been developed to measure the impacts of products or processes and better understand the potential effects they may have. One such tool is an LCA which quantifies the environmental, and sometimes social consequences of a product or process from a holistic life cycle perspective. The results of an LCA can be used to identify hotspots of poor environmental performance for improvement, to aid decision makers in developing environmental strategies, or serve as a marketing tool for companies to showcase the sustainability of a product to consumers. There have been several guidelines and standards developed by public and private organizations for LCAs, however the leading standard is ISO14044, and these are the standards used for this research (PRe, 2012).

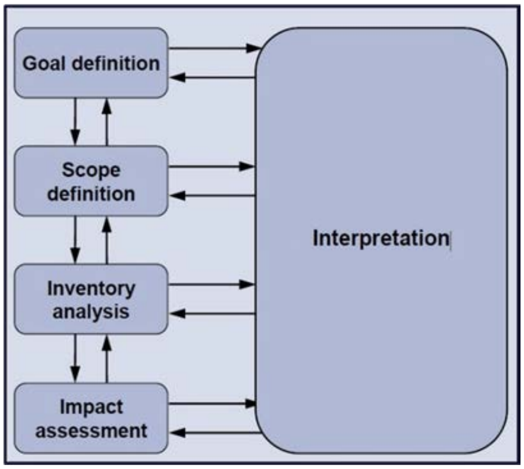


Figure 3. The phases and process flow of an LCA.

An LCA is carried out in four stages, including the i) goal and scope definition, ii) inventory analysis, iii) impact assessment, and iv) interpretation, as visualized in Figure 3. In the first phase, the overall goal and reason for carrying out the study is explicitly outlined. This includes details such as who the target audience is, what the intended application of the results are, who is commissioning or funding the study, and the decision-context. The scope definition phase elaborates upon this goal by explaining in detail the product or system that is to be studied and the choices in methodology for the following phases. These choices in methodology include defining the function, functional unit, reference flows, system boundaries, impact categories, handling of multifunctionality, choice of life cycle inventory (LCI) modelling framework and data quality requirements (ILCD, 2010).

The second phase is the LCI analysis, in which the necessary data is first collected for reference flows and then modeled as to how these flows move within the system. Primary data, or firsthand data from producers, should ideally be collected and secondary or generic data should only be resorted to when primary data cannot be obtained. The input and output data can then be applied to the modeled flows within the system. In the following impact assessment phase, the LCI results are translated into impacts by using impact factors for each respective impact category. In the last phase, these LCIA results are interpreted and assessed as to whether the goal of the study has been achieved. LCAs are an iterative process, and if issues in parameters, assumptions, or reference flows are identified during this interpretation phase, a re-iteration is performed in which the addressed issues are re-evaluated and adjusted accordingly. When a sufficient interpretation is reached, recommendations can be made based on the results (ILCD, 2010).

Types of LCAs

There are two types of LCAs, attributional LCAs (aLCA) and consequential LCAs (cLCA), which serve to answer different questions. An aLCA is purely an accounting method and quantifies the total emissions from the processes and materials used in the production, consumption, and disposal of a product. Attributional LCAs are useful to understand the mutual responsibility of all products and co-products for the impacts along their supply chains. A cLCA more thoroughly investigates how the environmental impacts of an entire system would be affected by a marginal change in the output of a product. This type of LCA typically requires economic modeling of inputs, prices elasticities, supply, and market effects of co-products, and also takes into consideration indirect effects of changing the output of a product. The results are meant for policy makers or decision makers to assess the (global) impacts that a certain policy or decision can have, which differs from an aLCA which focuses on a product rather than the complex interactions within a larger system (Tipper, Hutchison, & Davis, 2008). It is important to first understand the goal of a LCA study before choosing which type of LCA and methodology to apply.

2.2 MSW Treatment Technologies

Refuse Derived Fuel Production

In the MSW treatment technologies to be investigated, the MSW received at the plant is typically first processed to refuse derived fuel (RDF) in order to homogenize the feedstock and increase downstream efficiencies. MSW can be extremely heterogeneous and high in moisture, therefore processing it to RDF ensures a fuel input that is more homogenous and of a higher calorific value. Although RDF does not have a standardized definition in the EU, it can be generally referred to as the “segregated high calorific fraction of processed MSW”. Processing techniques may slightly vary, but typically the first step is to separate the recyclable fraction such as metals, and the inert fraction such as glass. The wet organic fraction is also separated to decrease the moisture content and can either be composted or anaerobically digested for biogas production. The remaining fraction, composed of primarily paper, non-recyclable plastics, textiles, and other materials may then be shredded or reduced in size to optimize handling. This fraction is referred to as RDF and can be used directly as a fuel input for incineration and gasification (EC, 2003). It is important to note that RDF contains the non-recyclable components of MSW and in theory does not infringe upon recycling which is higher than recovery in the waste hierarchy.

Incineration

The incineration of waste is defined as the combustion and complete oxidation of solid waste fuel, and can reduce the mass by 65-80% and volume by 85-90% (Lynn, Ghataora, & Dhir OBE, 2017). The combustible fraction is volatilized to a gas which is then combusted at a temperature of approximately 850°C, producing a flue gas and heat. The heat is then used to produce high-pressure steam which drives a steam turbine, and when coupled with a generator, produces electricity. In a combined heat and power incineration plant, both electricity and heat are produced in tandem, with the heat typically being distributed to neighboring industries or households via district heating (World Energy Council, 2016). The flue gas, which consists of carbon dioxide and impurities such as sulfur dioxide, dust and soot, as well as nitrogen oxides, heavy metals, and unburned hydrocarbons, is cleaned before being released into the atmosphere to meet emission requirements (EEW, n.d.). This is commonly done using ammonia to control NO_x emissions, lime to control for SO_2 and HCl, and injecting carbon to capture the heavy metals. Other solids are then filtered out and result in a solid residue known as fly ash. The incombustible fraction, which typically consist of ferrous and non-ferrous metals, glass, and other inorganic materials, also produces a solid residue, referred to as bottom ash DEFRA, 2013). Bottom ash accounts for 80-90% by mass off the residues and fly ash and air pollution control residues comprise the remainder (Lynn et al., 2017).

Gasification

The process of gasification differs from incineration in that the waste is treated at higher temperatures ranging from 600-1000°C and is performed in the presence of little to no oxygen. The controlled amount of oxygen that is introduced allows for partial combustion, providing the required heat for the gasification process. The resulting gas is raw synthesis gas, or syngas, which consists of primarily of H_2, CO and to smaller extent CO_2, H_2O, as well as other hydrocarbons such as CH_4, C_2H_4, benzene, and tars. If the reactor is fed by air opposed to pure oxygen, the resulting gas will contain some nitrogen and is referred to as producer gas (van der Drift & Boerrigter, 2006).

For RDF, fluidized bed gasifiers are typically used because entrained flow reactors require particle sizes less than 0.15 cm for optimum heat transfer. With fluidized bed gasifiers, solid particles are suspended in a gas or liquid and are changed into a fluid-like state. When the upward gas velocity exceeds the minimum fluidization velocity, bubbles are created in the bed which intensely mixes the bed particles which is ideal for high mass and heat transfer rates (Materazzi, 2017).

Gasification-to-Energy

For electricity generation, the gas purity requirements are less stringent than for the upgrading to fuels or chemicals. Regardless, the resulting producer gas from gasification still requires some cleaning before it can be combusted. The cleaning process involves the removal of problematic tars, particulate matter, and other impurities. Gas used in boilers for steam cycles require less extensive treatment than if used in gas engines or turbines (Hofbauer, Rauch, & Ripfel-Nitsche, 2007). Consequently, gas cleaning designs can highly vary, but typically involve the use or combination of physical removal by filters or scrubbers and catalytic processes. The clean syngas, comprised mainly of H_2 and CO, can then be used in a conventional burner or more efficient gas turbine to generate electricity (World Energy Council, 2016).

Gasification-to-Methanol

As for methanol synthesis, the requirements for syngas purity are more stringent and require an additional conditioning step. The cleaned syngas is first processed in a conditioning unit that shifts the gas composition to obtain a methanol module number, defined as $[H_2 - CO_2]/[CO_2+CO]$, to approximately 2, and a CO_2: CO_2+CO ratio in the range of 0.2 to 0.5. Inert compounds such as methane, nitrogen, and argon must also be removed (Salladini et al., 2018). Methanol is then synthesized from the clean and conditioned syngas, most commonly with a low-pressure catalytic reaction that has a selectivity greater than 99%. The catalysts most widely used commercially are copper-zinc oxide with aluminum or chromium oxides. They are quite sensitive to poisoning by sulfur and chlorine impurities and liquid water, thus their average industrial lifetime is two to five years (Lücking, 2017).

3. Background

3.1 MSW in the Netherlands

The Netherlands is one of the leaders in the EU regarding sustainable waste treatment and have surpassed EU waste targets more than a decade ahead of time. The Waste Framework Directive called for 50% recycling rates by 2020, and by 2009, the Netherlands already achieved this (EEA, 2013). Since then however, the recycling rates of MSW specifically have only climbed to 53% in 2016 (Eurostat, 2016). Of the unrecycled fraction of MSW, over 97% is incinerated for energy and material recovery and only 3% is landfilled (1.4% of total MSW treated) (Eurostat, 2018). Energy is recovered in the form of heat and electricity; the heat is typically provided to local greenhouses, households, or industries, and the excess electricity remaining after internal use is distributed to the local electrical grid (Rijkswaterstaat, 2017).

The Netherlands is also a leader in the treatment of incineration residues. In 2016, of the 1.5 Mt of residues generated from WtE plants, 94% was reused and only 6% landfilled (Vereniging Afvalbedrijven, 2016). The bottom ash has two types of qualities and is most commonly used as road construction material. However, the more toxic type of ash requires layers of polyethylene to isolate the materials from the soil and prevent leaching when used as road fill. The government and waste incinerators have agreed that as of 2019, bottom ash can no longer be used in isolation quality and must meet the requirements to be a freely applicable material. Bottom ash is also used as an aggregate in the concrete industry, although the quality typically needs to first be improved by washing or accelerated aging with CO_2. The fly ash, which tends to contain far more toxic pollutants is either used as a filler in asphalt, immobilized and landfilled, or is exported to Germany to fill in empty salt mines (Joost de Wijs, personal communication, May 23, 2018).

3.2 Energy and Methanol in the Netherlands

Electricity and Heat Production

The Netherlands still heavily relies on fossil resources for electricity and heat production. In 2016, 46% of electricity was generated from natural gas, 32% from coal, and only 13% from renewable sources such as wind, solar, waste incineration, and biomass co-firing (Energieonderzoek Centrum Nederland, 2017b). As for heat production, in 2015, 87% of household heat came from natural gas and only 6% from biomass. For industry which requires higher temperature heat, 43% came from natural gas and nearly 30% from petroleum products and coal (ECN, 2017a).

Since then however, the Dutch government has set ambitions to reduce direct GHG emissions of the energy supply by 49% in 2030 compared to 1990 levels. This exceeds the requirements put forth by the EU Renewable Energy Directive, which has a binding target of a 40% reduction in GHGs by 2030 compared to 1990 levels, as well as a target of 27% renewable energy in 2030 (European Union, 2018). These policies will drive the growth in renewables in the coming decades. The Energy Research Institute of the Netherlands' (ECN) forecasts future electricity generation even exceeding some of these targets. Their models project that in 2030 the electricity mix will consist of 46% wind, 11% solar, and less than 30% from natural gas and coal (ECN, 2017). Such figures are harder to predict for a time horizon as far as 2050, but the EU Energy Roadmap to 2050 has demonstrated in many of its scenarios that the power sector can almost entirely eliminate emissions by 2050 (EC, 2012). Due to the future increase in production and decarbonization of electricity, it is also expected to replace fossil fuels in the heating sector by 2050, both in the form of electric furnaces and electric or hybrid heat pumps. In the short term, however, natural gas will slowly replace more carbon intensive fossil sources such as coal and petroleum products for heat and electricity production (EC, 2011a).

Methanol Production

Globally, the majority of methanol is produced via natural gas reformation and only a small percent is produced with coal, in countries like China who want to use cheap domestic fossil fuels to reduce dependence on imports. In the process of synthesizing methanol from natural gas, the gas is first purified by separating and removing sulfur compounds. The resulting methane can then be reformed to syngas via either steam reforming or autothermal reforming. For steam reforming, high temperatures of 800-1000°C are needed, and the process is highly endothermic, thus requires natural gas both as a feedstock and heat source. For autothermal reforming, a combination of steam reforming and partial oxidation is used to balance the production and consumption of heat. Partial oxidation is performed at temperatures of 1200-1500°C but is highly exothermic and requires a H_2/CO ratio of 2. For both reforming routes, the conditioned syngas is then converted to methanol in a similar manner than with syngas from waste gasification, as explained previously (Landälv, 2017).

The Netherlands is quite unique in the EU in terms of methanol production, as they are one of the only countries commercially producing bio or green methanol. BioMCN has a commercial plant in Delfzijl with an annual capacity of 450 kton of biomethanol and has recently announced plans to re-open its second production line, expanding production another 480 kton. Opposed to natural gas, this plant uses either crude glycerin, a by-product of biodiesel production, or biogas, which can both be considered biogenic waste feedstocks (BioMCN, 2014). Nevertheless, the chemical industry in the Netherlands has expressed the ambition to reduce GHG emissions and transition to cleaner and more resilient ways of production. The Association of the Dutch Chemical Industry (VNCI) has developed roadmaps for 2030 and 2050 outlining various pathways for GHG reductions in the sector. The ambition for 2030 is to reduce emissions 50% compared to 2005 levels, and in line with the EU target, aims to reduce emissions 80-95% by 2050 compared to 1990 levels. The three themes of these roadmaps are circular and biobased, electrification, and carbon capture utilization (CCU) or storage. These are all relevant to the case of methanol production, for which several sustainable alternatives will exist in the future. In the same way that MSW is gasified, lignocellulosic or other waste residues can produce a bio-syngas for upgrading to biomethanol. As for electrification, it is assumed in the 2050 roadmap that all electricity will come from carbon neutral sources, and that this renewable electricity could be used to electrolyze water and produce renewable hydrogen and oxygen. The renewable hydrogen could then be used as a feedstock for methanol production, which would also require a CO_2 source for the reaction. In 2050 there are several sustainable options for where this CO_2 can be obtained from. It could be collected from other industries emitting CO_2, although this could become scarce as other industries simultaneously decarbonize. Alternatively, CO_2 could be collected from the atmosphere from direct air capture (DAC), but this also has its downfalls because it is proven to be quite energy intensive. Although it is assumed that this required energy will be renewable, it is still debatable whether this amount of renewable energy should be prioritized for DAC. Another more viable and potentially more likely option is to utilize emissions from biomass combustion, which unlike the other two sources, is renewable in nature (Ecofys and Berenschot, 2018).

Methanol has a large expanse of end uses, as shown in Figure 4, which displays the different end uses globally in 2015. It is apparent that methanol is used more so as a chemical than as a fuel; it is primarily used as a building block for formaldehyde and olefin production, and these chemicals can then range in application from chemicals to plastics to fibers. Only 28% is used for fuel blending or upgrading to fuels, including petrol blending, MBTE, DME, and biodiesel (Alvarado, 2016). It is important to note that Figure 4 shows global use of methanol, and this may slightly vary in the Netherlands specifically. The end uses may also change to a varying degree in the future depending on different policies or market demands. For example, historically methanol was used in fuels to a very small extent but experienced an annual growth rate of 25% from 2000 to 2015 due to blending mandates in China (Alvarado, 2016).

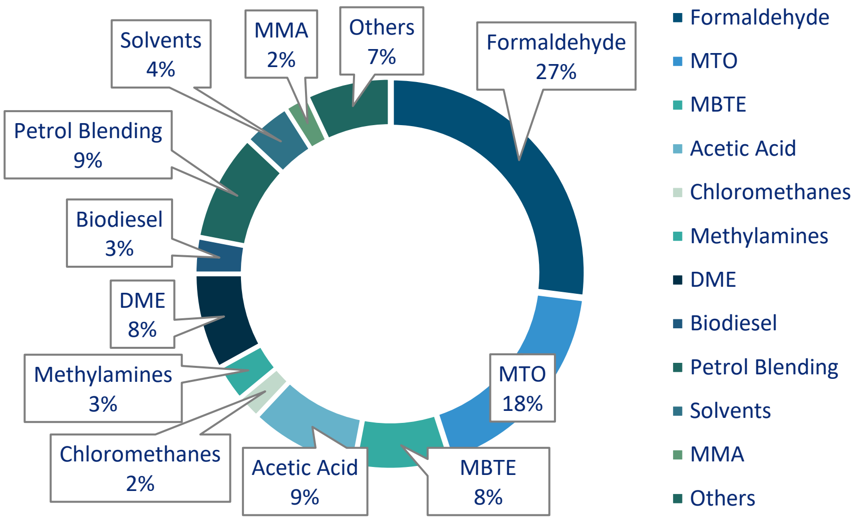


Figure 4. End uses of methanol globally in 2015.

4. Methods

4.1 Goal and Scope

The goal of this study is to contribute to the conversation of waste management and demonstrate the potential best treatment of MSW is in terms of climate change mitigation, now and in the coming decades. To achieve this, an aLCA is performed that quantifies the GHGs associated with two different WtE technologies, incineration and gasification, and the emerging gasification-to-methanol technology. This LCA assumes that the electricity, heat, and methanol produced via incineration or gasification directly substitutes a comparable product in the market, which is referred to as the reference product. The substitution of the average technology rather than the marginal technology is assumed, and indirect effects are not considered. The difference in emissions between the product assessed and the substituted product is thus not a claim of actual emission reductions or increases as is done with a cLCA. Rather, it is comparison between the two products, and still serves as a useful indication of which treatment could be better than another in certain circumstances. A comparative analysis of the waste treatment options is made, and the results are intended to serve as recommendations to policy or decision makers which treatment may be optimal in the circumstances specific to this study. The geographical and temporal scope are narrowed to the Netherlands in 2020, 2030, and 2050 because of the recent announcement of the Enerkem waste-to-methanol plant to be built in the Port of Rotterdam (Enerkem, 2018). An LCA is performed for various years to study how the optimal use of MSW may change depending on the transitioning and decarbonization of the chemical, energy, and biobased material sectors. For 2020, the reference technology assumptions are based on forecasts of the electricity, heat, and methanol markets and respective life cycle GHG intensities. For 2030 and 2050, two scenarios are built to demonstrate potential paths of reference technology developments.

Functional Unit

This research aims to assess various MSW treatment options and demonstrate a potential best use in terms of climate change mitigation. The treatment options under consideration, however, provide different services such as electricity production versus methanol production. Thus, for these options to be accurately compared the functional unit should be the treatment of MSW. A unit of MSW can be expressed in a variety of ways, such as mass, volume, energy, price, or other unit of measure. Furthermore, MSW can also be defined or categorized in various ways depending on the organization collecting the data. It can also highly vary in composition and energy content depending on the time of year it is collected or the location it is collected from (World Energy Council, 2016). There is the added complication that some waste treatment facilities pre-treat MSW to produce RDF while others incinerate it directly as received. In the Netherlands however, it is expected that in 2020 waste treatment facilities will pre-treat waste as described in the MSW to RDF production section. To ensure a standardized and consistent functional unit, this study uses 1 metric ton of average RDF treated in the Netherlands as the functional unit. The standardized characteristics of the RDF are outlined in Table 2. The carbon content, and biogenic and fossil fractions are taken from the Ecoinvent database for MSW in the Netherlands and the lower heating value (LHV) has been adjusted to reflect predicted values for 2020, as will later be elaborated upon.

Table 2. Assumed parameters of RDF considered for the functional unit for 2020.

Parameter	Unit	Value
Lower heating value (LHV)	MJ/kg	14.0
Biogenic Fraction	%	61
Fossil Fraction	%	39
Carbon Content	% (wet basis)	33.5

4.2 Life Cycle Inventory

Boundaries

The boundaries of the production phase of the life cycle begin with pre-treated RDF and end at the gate of the energy or chemical plant, as outlined in Figure 5. They include the incineration or gasification of RDF, and all of the following processing steps to the final product of electricity, heat, or methanol. It is presumed that in the processing to RDF, all incombustible recyclable materials such as glass and metal have been removed and are not present in the bottom ash. These ashes, as well as other incineration residues are reused in the Netherlands, either in the construction industry as road fill, or as an aggregate in the cement industry. Since these residues have no energetic value and little economic value, no emissions are allocated to them neither assume any avoided emissions. The boundaries begin with RDF at the plant, thus emissions from transport of the MSW to the plant is not taken into consideration, as this would be done regardless of the treatment pathway.

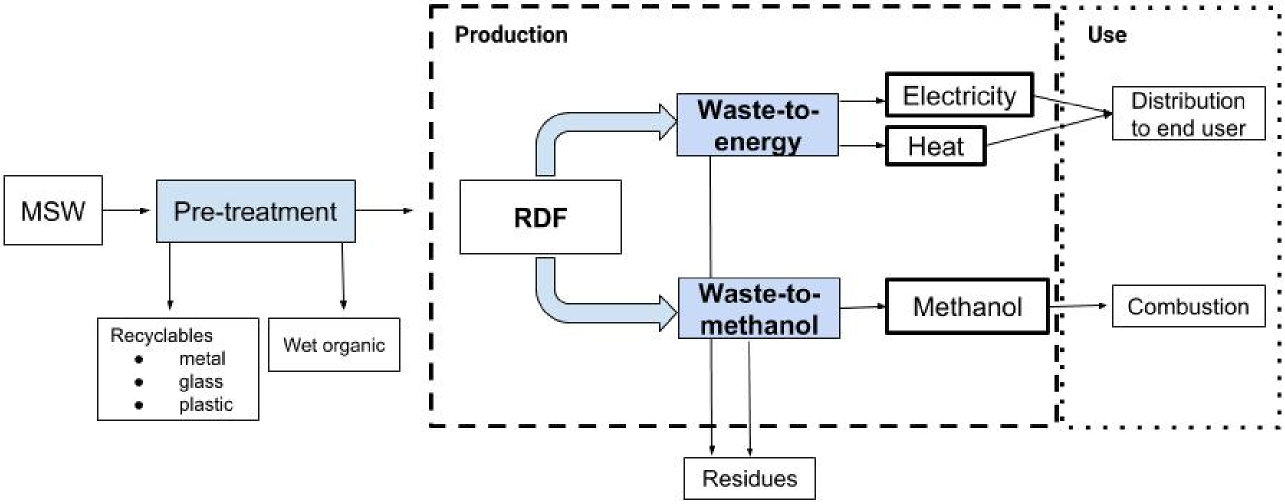


Figure 5. System boundaries of the LCA from RDF to plant gate. Dashed line indicates LCA boundaries of production phase, dotted line indicates use phase.

An LCA is performed for both the production and use phase, and the effects of this choice will be later discussed. The production phase encompasses all the processes within the dashed line, and the use phase includes those within the dotted lines. For electricity, the use phase includes the transmission from high to low voltage and distribution of electricity to the end user and for heat it accounts for the distribution losses of physically delivering heat from the plant to households. As for methanol, a simple use phase is assumed in which the methanol is ultimately combusted. In the Netherlands where the majority of waste is incinerated, it is assumed that regardless of the end application of methanol, these products would sooner or later be combusted after they are disposed of.

Allocation

In the case of multifunctional processes, the allocation of the co-products must be properly explained and justified. For the WtE pathways, the co-products of heat and electricity are generated. Allocation is avoided by system expansion, and both electricity and heat are accounted for in the system rather than allocating burdens to one product or the other based on an energetic or economic basis. Since the by-product of residues are outside the boundaries of the system for both WtE and WtM, allocation does not need to be considered. For methanol production, the by-product of steam is assumed to be used internally for energy.

Data Collection and Reliability

The data collected for the LCI is gathered from industry experts, through a literature search, and from the Ecoinvent 3 database. Primary data from existing incineration and gasification plant is used where possible, and these plants are chosen based on which ones would serve as a good representation of a plant operating in the Netherlands in 2020, as this is the geographical and initial temporal scope of the LCA.

Incineration

In the Netherlands, the plant that incinerated the largest amount of waste in 2016 and previous years is the Afval Energie Bedrijf (AEB) Amsterdam plant in North Holland. This company is at the forefront of cutting-edge technology and innovation for WtE solutions and has the greatest efficiency of Dutch WtE plants (Rijkswaterstaat, 2017). Therefore, data was obtained from the AEB Amsterdam plant in 2016, serving to represent the technology and efficiencies of incineration in the Netherlands in 2020. The data was collected from the 2016 Annual Report from AEB, as well as through personal communication with Joost de Wijs, advisor of the Dutch Waste Management Association (Vereniging Afvalbedrijven) and business developer at AEB.

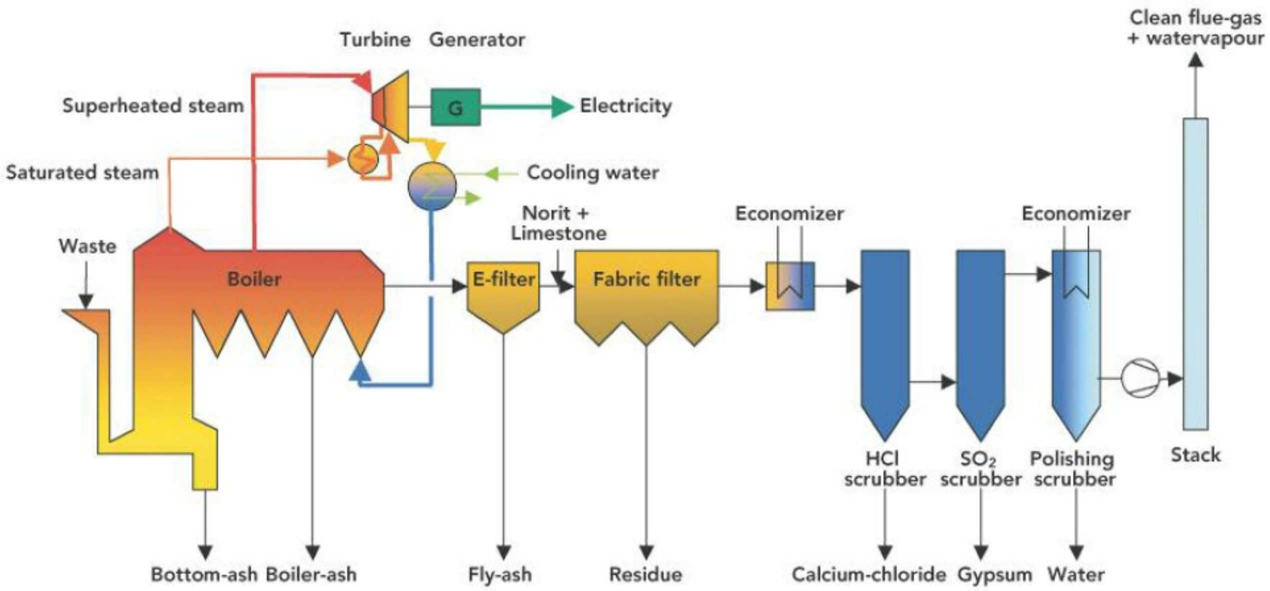


Figure 6. Process schematic of waste incineration at the AEB plant.

The general process of incineration at this plant can be seen in Figure 6 above. Not included in the schematic is the processing of MSW as received to RDF, although this is not included within the boundaries of the LCA as explained previously. The Dutch incineration process from the Ecoinvent database is used as a template and adjusted accordingly to reflect the efficiencies, chemical use, waste composition, and other aspects specific to the AEB plant. For the cleaning steps, it is assumed that activated carbon and limestone are inputs in the E-filter, and ammonia, sodium hydroxide, chromium and titanium oxide are used for cleaning the flue gases (AEB, 2017). The wastewater is assumed to be treated with hydrochloric acid, iron chloride, and organic and inorganic chemicals as defined by Ecoinvent. Lastly, an important assumption is made that all of the carbon contained in the waste is emitted as CO_2; the biogenic fraction is considered carbon neutral, and only the fossil carbon contributes to the calculated burdens of the LCA.

Gasification-to-Energy

There are currently no commercial scale gasification-to-energy plants in the Netherlands that use MSW or RDF as a feedstock. There are some commercial plants that gasify other feedstocks, such as ESKA in Hoogezand which uses wastes from its own paper production to produce energy for internal use (Grootjes, 2018). Due to the lack of an existing Dutch plant, primary data from 2014 from a comparable gasification plant in Finland is used. This is Lahti Energy and Valmet's Kymijärvi II power plant, which is the world's first gasification plant to use waste as a feedstock and has been operational since 2012. This plant was chosen to model in the LCA because Lahti claims to have the best gasification expertise in the world, and serves as a close representation of a waste gasification power plant to theoretically be built in the Netherlands in 2020 (Isaksson, n.d.).

The Lahti plant has a capacity of 160 MW and the gasifier is a circulating fluidized bed gasifier that is 25 meters high with a diameter of 5 meters, with the bed composed of sand and lime. Gasification is performed at a temperature of 850 to 900°C and the gas is cooled to 400°C using water, then cleaned with mechanical hot filtering. The filtering process does not appear to use any chemicals, rather the impurities are physically filtered, and the solids are removed with pulses of nitrogen gas by the unit shown in Figure 7 (right). Natural gas is not needed for the reaction as it is highly exothermic, but there is still approximately 655 MJ/t RDF used for startup and backup for the gasifier (Lahti Energia, n.d.).

Figure 7. The Lahti Energy Kymijärvi II waste gasification plant (left) and gas cleaning filter (right).

The overall process produces bottom ash, fly ash, and filter ash; the bottom ash consists of fuel and bed materials, the filter ash of carbon and impurities from the gas, and the fly ash of impurities from the flue gas after combustion (Lahti Energia, n.d.). As noted earlier, these residues are not included within the boundaries of the system and are assumed to be fully reused. Like incineration, all of the carbon contained in the waste is assumed to be emitted as CO_2 with the biogenic fraction considered carbon neutral. Much of the carbon in the waste may first be contained in the heavier gases and problematic tars that are formed during gasification, however, these are typically burned for energy eventually; therefore, it is assumed this carbon is eventually emitted as CO_2.

Gasification-to-Methanol

There is one commercial gasification plant in the Netherlands that produces methanol. However, this plant gasifies glycerine to produce biomethanol, so data from this plant could not be used for this LCA, since it is rather investigating the use of MSW as a feedstock. General technology and process efficiencies are thus used from the Enerkem plant in Edmonton, Canada. This plant, which began the production of methanol in 2015, processes RDF and has a capacity of 38 million liters per year. Marie-Hélène Labrie, Senior Vice-president of Government Affairs and Communication for Enerkem was interviewed as well as Rob Vierhout, an independent advisor for Enerkem, to obtain data and further information about the Edmonton and future Rotterdam plants. As seen in Figure 8, the gasifier is a bubbling fluidized bed gasifier and the primary syngas is cleaned with scrubbers and conditioned before proceeding to the catalytic reactor. Both of these processes are proprietary, and details could not be shared for this research because of intellectual property conflicts. What is known is that in order to manage technology risks, Enerkem decided to use existing commercially available catalysts rather than developing novel ones themselves (Marie-Hélène Labrie, personal communication, April 19, 2018). The most common commercially used catalysts are copper-zinc and aluminum oxide, which are produced by companies such as BASF, Shell, and DuPont, thus these are the assumed catalysts for the LCA (Lucking, 2017).

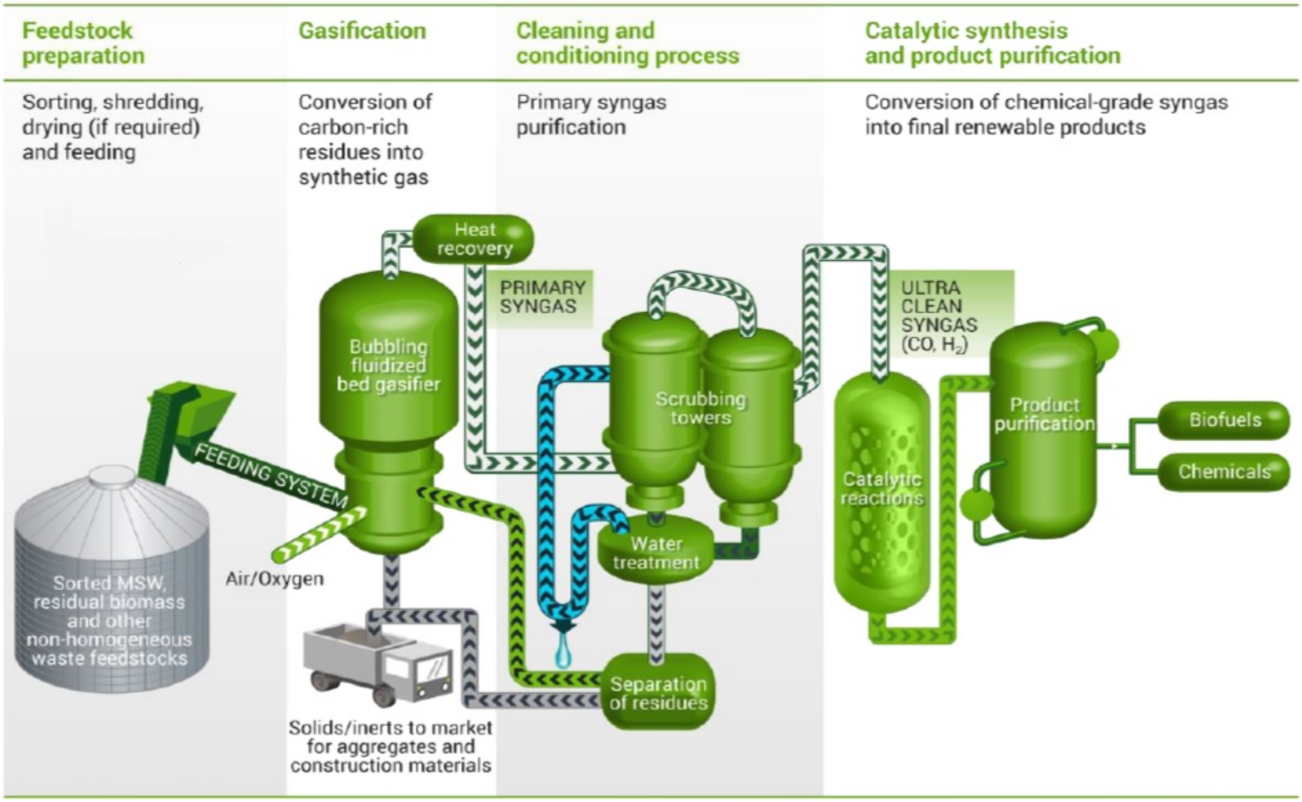


Figure 8. Process schematic of Enerkem's waste-to-methanol technology.

The efficiency of the overall process is 600 liters of methanol per bone dry metric ton of RDF at the Edmonton plant, but could vary for other facilities, as reported by the contacts at Enerkem. The net energy use could also not be disclosed, although Enerkem confirmed that the only auxiliary energy used is electricity for utilities and a small amount of natural gas for start-up and thermal oxidization. Electricity use in conventional methanol plants is negligible, typically only 0.074 kWh/kg methanol, so this is not included in the LCI (Swiss Centre for Life Cycle Inventories, 2007). The amount of natural gas used is assumed to be the same as the Lahti gasification plant. As for the treatment of residues, in the Edmonton plant some of them can be reused for construction material while other inerts are landfilled (Marie-Hélène Labrie, personal communication, April 19, 2018). It is assumed that in the Rotterdam plant, these residues are reused as is done with incineration and remain outside of the boundaries of this research. Based on the reported efficiency and mass balance calculations, it is assumed that 53% of the carbon contained in the waste is ultimately embedded in the methanol. The remaining 47% is assumed to be emitted as CO_2 during the gasification process, as the syngas to methanol step has an efficiency greater than 99%. Hydrogen and steam are also produced during this step, but Enerkem does not sell steam nor hydrogen, thus the steam is assumed to be used for internal energy use and the hydrogen for gas conditioning. It is unknown what ratio of air and oxygen is used for the gasification step, and whether the Enerkem process is oxygen deficient. It is assumed that no external oxygen needs to be purchased, and the uncertainty and sensitivity of this is acknowledged.

Scenarios

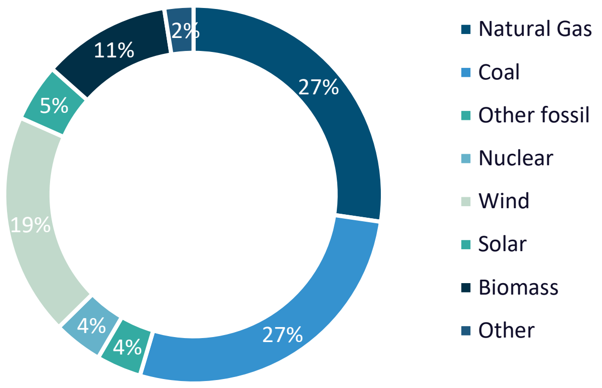
For each LCA, the reference energy or methanol is determined and is then compared with the RDF derived equivalent. The references are the energy and methanol assumed to be replaced by the from RDF incineration or gasification, thus the life cycle GHG emissions from these reference technologies are considered as avoided emissions. Since this study performs an aLCA opposed to a cLCA, the avoided emissions cannot be claimed as the actual emission reductions that would occur in reality because the reference product is the average rather than marginal product. The avoided emissions can thus be interpreted as the emissions avoided *if* these were to be the reference energy and methanol replaced by the RDF based equivalent in such a scenario.

Identifying the feedstocks or fuel mixes for the reference electricity, heat, and methanol production can be difficult to predict for time horizons as far as 2030 and 2050 because they are influenced by a multitude of factors such as policy, energy prices, industry targets, cost effectiveness of alternatives, amongst others. These factors are not only hard to accurately predict themselves but can also have complex interactions and feedbacks within the larger energy and chemical systems. Thus, two scenarios are developed to demonstrate, rather than predict, the ways in which these markets can develop in the Netherlands. The first scenario is the *Business-as-Usual (BAU) Scenario* which aims to reflect the expected developments of electricity, heat, methanol, and RDF composition and processing based on current and expected policies and pace of market and technological developments. It serves to demonstrate a future in which the energy, methanol, waste, and related sectors continue business-as-usual and follow the trajectory that is currently forecasted. The second is the *Breakthrough Scenario* which is built to demonstrate the future to unfold if the ambitious GHG targets of the energy and chemical industries are achieved as well as ambitious developments in biobased materials. In essence, it is meant to represent a future in which decarbonization of the economy is highly prioritized and accelerated beyond current expectations. For 2020, scenarios are not built as this is only a few years away, and accurate predictions are simpler to make. The assumptions and corresponding justifications for each year and scenario are further elaborated in the subsections below.

Time Horizon 2020

In 2016, of the energy generated at the AEB incineration plant from MSW (excluding the sludge that was treated from the neighboring sewage plant) 83% was electricity and 17% heat (4.9:1 ratio on an energy basis). The ratios of electricity to heat production for WtE plants in the Netherlands, however, range vastly from 0.04:1 to 9.9:1 (Rijkswaterstaat, 2017). This broad range could be influenced by the demand for district heating at each location, the prices of heat versus electricity, or even technological restraints. The ratio is thus chosen to reflect that of the gasification plant so that incineration and gasification can be fairly and accurately compared. For the Lahti gasification plant, the ratio of electricity to heat in 2014 was 0.5:1., thus for the LCA the ratio of electricity to heat is assumed to be 0.54:1 for both technologies (35% electricity and 65% heat). As for the overall energy efficiency, the newer of the two systems at AEB had an overall efficiency of 31% for heat and electricity in 2016, and the LHV of the waste treated was relatively low, at 11.1 MJ/kg. This was a result of there being no pre-treatment of MSW to RDF in this year, and incombustible material such as ferrous and non-ferrous metals in the RDF resulted in a relatively low LHV. In 2017, however, AEB built a new sorting plant to remove recyclables such as metals and plastics which is expected to increase the LHV of the waste treated (Joost de Wijs, personal communication, May 23, 2018). For the Lahti gasification plant, the overall efficiency was 74.8%, and had a higher LHV of 13.8 MJ/kg of the waste treated. To accurately compare these two technologies, and to also reflect the calorific value of the waste to be treated in 2020 when pre-sorting and treatment are expected to take place, the LHV of the waste is assumed to be 14 MJ/kg for both technologies. The assumed efficiency of incineration is 42% and for gasification is assumed to remain at 74.8%. For methanol production, efficiencies provided by Enerkem are utilized, therefore 1 ton of RDF is assumed to produce 600 liters (10.8 GJ) of methanol (Marie-Hélène Labrie, personal communication, April 19, 2018).

The GWP of electricity, heat, and methanol produced with these technologies are then compared to the average reference products they are assumed to replace. For electricity, this is assumed to be the national grid mix, and for heat this is assumed to be the average national mix provided to households. The electricity mix of the grid in 2020 is based on the projections of the Dutch Energy Outlook or “Nationale Energieverkenning 2017” (NEV). The projections in the NEV are a bottom-up analysis that uses a complex model that integrates social, economic, technological, and political factors to construct the future Dutch energy landscape up to 2030. It aggregates a combination of models from different departments of the government such as the Enterprise Agency (RVO), Energy Research Center (ECN), and Environmental Assessment Agency (PBL). Thus, it offers a very robust and holistic model for reference energy production for the LCA. For electricity, the report projects that coal and natural gas will comprise 54% of the mix, with wind leading as the largest renewable source, accounting for 19% of the mix, as shown in Figure 9. The heat for 2020 is based off the fuel mix of household heat production in 2015 (ECN, 2017). Although the Dutch government has recently announced the ambition to have all residential buildings gas-free by 2050, the effects of this will only be seen in future decades (van den Ende, 2017). Therefore, for the LCA in 2020, natural gas is still assumed to represent 87% of heating fuel, with biomass and heat from combined heat and power at 5.8% and 3.7% respectively, as outlined in Figure 10 (ECN, 2017). Methanol is assumed to be produced from 100% natural gas, as this is the current standard practice in Europe and is not expected to change before 2020 (Ecofys and Berenschot, 2018).



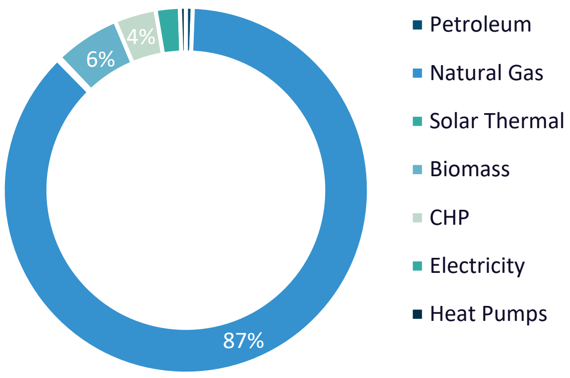


Figure 9. Reference electricity production mix in 2020.

Figure 10. Reference heat production mix in 2020.

Time Horizon 2030

In the 2030 BAU Scenario, the reference electricity and heat mixes are also based off projections from the NEV. These projections are used for this scenario because they can be considered as a BAU scenario in which energy evolves as expected, thus reflect well the desired characteristics of this scenario. It is projected that natural gas use reduces by 16% from 2020 to 2030 for electricity production and is replaced by growth in wind and solar to shares of 46% and 11% respectively. Biomass represents 6% of the share, and it must be noted that this also includes the incineration of MSW but amounts to only 16% of this 6% share. The effect of double counting MSW in the RDF treatment and reference energy is however negligible for the overall GHG intensity. As for household heat, the expected share of natural gas, electric heat, waste heat, and oil are 80%, 13%, 6%, and 1% respectively (ECN, 2017). Methanol production for chemical use in this scenario uses projections from the Roadmap for the Dutch Chemical Industry to 2050. In this roadmap, the ‘Plausible pathway 1: 2030 compliance at least costs scenario’ projects that methanol will be produced via 100% natural gas. As the title suggests, this scenario was built assuming that the most cost-effective measures are adopted using 2017 energy prices, and serves as a good representation for a BAU outcome (Ecofys and Berenschot, 2018).

The 2030 Breakthrough Scenario assumes that for the reference heat, the target for a 49% reduction in GHG emissions from 1990 levels is achieved by 2030. Since the 1990 figure on a life cycle basis for heat could not be obtained, it is assumed that there is a 20% decrease in GHG intensity of heat from 2020 to 2030 (assuming that the balancing 29% of the target reduction is achieved between 1990 and 2020). For electricity production, it is assumed that the government sticks to their promise of banning coal-fired plants by 2030, and that all coal is replaced by natural gas. As for methanol, the Dutch chemical industry aims to reduce emissions by 50% in 2030 compared to 2005 levels (Ecofys and Berenschot, 2018). Since there is not an LCA EF in 2005 for methanol specifically, it is arbitrarily assumed that there is a 20% reduction in 2030 compared to 2020 levels, assuming that methanol is decarbonized linearly from 2005 to 2030. The 20% reduction arises from the increased use of biomass, specifically wood chips from forestry, industry, and waste wood.

The changes made to the RDF technologies in this year are a 5% increase in incineration and 1.5% gasification energy efficiencies. Although for incineration the AEB plant is near the maximum electrical efficiency, this 5% improvement is assumed to be mostly from heat efficiency. The 1.5% improvement of gasification comes from the use of a reheat steam cycle which has not been demonstrated in gasifier plants as of 2018 but has the potential to do so by 2030 (Juhani Isaksson, personal communication, July 05, 2018). It is also assumed that 25% less natural gas is used for the startup and backup in gasification-to-energy and gasification-to-methanol compared to 2020 because it is assumed that technological hurdles will be overcome in this decade, and less startups of the gasifier will be required. The most significant change from 2020 is the change in composition of RDF, specifically the biogenic fraction. In the BAU and Breakthrough Scenarios, the fossil fraction of the waste is assumed to be reduced by 7 and 16% respectively. These values are taken from a study which estimated the substitution of fossil-based materials with biogenic ones in the EU in 2030 and 2050. The substitution rate is defined as the percent of fossil-based materials that are replaced by biogenic ones. The BAU Scenario utilizes the substitution rate of the 'Reference Scenario' developed in the study, which is very comparable because it is meant to illustrate a business-as-usual situation in which there are market developments for easy-to-reach biobased materials and no major developments for drop-in-biopolymers. The Breakthrough Scenario utilizes values from the study's 'Transition Scenario' which also serves as a good representation, as this scenario illustrates a very ambitious future with substantial advances in advanced biomaterials production (Schipfer et al., 2017). The biogenic fraction for the BAU and Breakthrough Scenarios are thus assumed to increase to 64 and 67% considering the substitution rates of fossil-based materials with biobased ones.

Time Horizon 2050

For the reference heat production in the BAU Scenario, the GHG intensity is based off a 2050 vision created by the Dutch Royal Association of Gas Companies (KVGN). In this vision, the majority of the Dutch residential sector is heated by district heating from geothermal and waste heat and electric and hybrid heat pumps. It is estimated that in 2050 there will still be 1 million out of 7 million homes that will use conventional boilers due to insufficient insulation for the viability of heat pumps, being located in an area of low building density, or in an area with limited space for the construction of underground pipes. Thus, there is still a share of 17% of natural gas, although this could arguably be substituted with biomass by 2050 (van den Ende, 2017). For electricity it is assumed that coal is entirely eliminated for electricity production and is replaced by an increased share in wind and solar, amounting to 59% and 15% of the mix. Natural gas and biomass remain at the same shares as in 2030, at 11% and 6%. For methanol, the 'Compliance at least costs scenario' is again used for the BAU Scenario of this study, and it projects that methanol will be produced from 100% biomass in 2050, although it not specified as to which biomass is to be utilized (Ecofys and Berenschot, 2018). It is first compared to biomethanol from wood chips, and biomethanol made from different types of biomass feedstocks is then be explored and further discussed.

For the Breakthrough Scenario, the target of 95% GHG reduction in electricity production compared to 1990 levels is assumed to be achieved. For heat it is assumed that there is a 75% reduction in GHG intensity of heat compared to 2020, considering that a 20% reduction was already achieved from 1990 to 2020. The reference methanol in this scenario is taken from the 'Direct Action and High-Value Applications' scenario of the Roadmap for the Dutch Chemical

Industry to 2050. This scenario mirrors the Breakthrough scenario well as it was built to also represent an ambitious future. It optimizes energy and feedstock use for the highest value while considering constraints of biomass use and availability. It also applies circularity to its fullest potential and follows the guidelines of the EU Waste Directive (Ecofys and Berenschot, 2018). With these considerations, the reference methanol is assumed to be CCU based methanol made with waste CO_2 and renewable hydrogen as feedstocks.

The changes made to the RDF technologies in this year are a 2% increase in incineration and 2% gasification energy production efficiencies. It is also assumed that 50% less natural gas is used for the startup and backup in gasification-to-energy and gasification-to-methanol compared to 2020. A significant change in assumptions is the biogenic fraction of the RDF, which reflects the estimates of biobased material substitution rates of Schipfer et al. (2017) in their Reference and Transition Scenarios. Again, the BAU Scenario uses rates from the study's Reference Scenario and from the Transition Scenario for this study's Breakthrough Scenario, as these are similar in nature. In 2050, there is a large divergence between the two scenarios, with a biobased substitution rate of 19% in the Reference Scenario and 72% substitution rate in the Transition Scenario. This results in the biogenic fraction of RDF in this study to be 68% for the BAU Scenario and 89% for the Breakthrough Scenario.

Emission Factors

For each decade, a GHG life cycle emission factor (EF) is used for electricity, heat, and methanol production to calculate the emissions of the reference products. The EFs of fuels for heat and electricity production are obtained from the Covenant of Mayors 2017 Version of LCA Emission Factors for fossil and renewable energy sources. These are the standard EF used by Member States that have committed to reducing their GHG emissions and are used to make calculations in their Sustainable Energy and Climate Action Plans. The LCA EFs account for emissions along the entire supply chain of each energy source, from the extraction of the fuel or production of energy to the end user (EC, 2017). This serves as a fair comparison to the electricity and heat generated by RDF incineration or gasification since the entire life cycle is also considered for these processes. It is important to note that such an approach also considers the entire life cycle of renewables, thus they are not considered completely carbon neutral as with the standard approach. They include the emissions from the material extraction and production of solar panels, wind turbines, etc.

For methanol, there is not such a default LCA EF as with energy. Thus, the life cycle GHG emissions are utilized from the Ecoinvent database for both methanol from natural gas and biomass. The Ecoinvent database assumes that methanol from natural gas consumes the average amount of natural gas for feed and fuel used in steam reforming, combined reforming, and autothermal reforming, which is 32.7 MJ natural gas/kg methanol. It is assumed the hydrogen purged is burned with no energy recovery and the emissions arise largely from the burning of natural gas as fuel in the furnace (Swiss Centre for Life Cycle Inventories, 2007). As for methanol from biomass, the Ecoinvent database assumes the gasification of 64% of wood chips from forestry, 22% wood chips from industry, and 14% waste wood chips. The majority of emissions arise from the production of bio-syngas which includes the drying, chipping, and transport of the wood chips. The remaining emissions come from the external electricity use in methanol synthesis and the overall emissions amount to 0.318 $kgCO_{2eq}$/kg methanol (Jungbluth et al., 2007).

Table 3. Overview of assumptions made in the BAU and Breakthrough Scenarios in 2020, 2030, and 2050.

Parameter	Unit	2020	2030		2050	
SCENARIO		*BAU*	*BAU*	*Breakthrough*	*BAU*	*Breakthrough*
Biogenic Fraction RDF	%	61	64	68	67	89
Reference Electricity	kgCO$_2$eq/kWh	0.436	0.264	0.198	0.118	0.033
Reference Heat	kgCO$_2$eq/kWh	0.261	0.248	0.209	0.116	0.065
Reference Methanol	kgCO$_2$eq/kg MeOH	0.767	0.767	0.614	0.261	0.226

Life cycle emissions of other biomethanols are also taken from literature as a comparison of the different biomass feedstocks that can be used. In a study that had similar boundaries, short rotation coppice and logging residues were found to have a 24 and 33% GHG reduction compared to conventional methanol production from natural gas, corresponding to EFs of 0.64 and 0.56 kgCO$_2$eq/kg methanol (Majer & Gröngröft, 2010). The life cycle emissions for CCU methanol, like for many other LCAs, can highly vary depending on the methodology, boundaries, and allocation selected in a study. Since it is an extremely immature technology, there are not yet standardized methodologies for CCU and these are still under development (von der Assen, Jung, & Bardow, 2013). The immaturity of CCU also means that LCA estimates are commonly made with process modeling and broad assumptions rather than from primary data from CCU plants. One such study modeled the production of methanol from renewable hydrogen and captured CO$_2$ as raw materials. It calculated the indirect and direct emissions of 0.09 and 0.136 kgCO$_2$/kg methanol, thus an EF of 0.226 kgCO$_2$/kg methanol is utilized for CCU based methanol (Pérez-Fortes, Schöneberger, Boulamanti, & Tzimas, 2016). An overview of the most critical scenario assumptions is provided in Table 3.

4.3 Impact Assessment and Interpretation

The impact assessment is performed using the software SimaPro and the only impact category examined in this study is global warming potential (GWP). Although this narrows the scope and is a limited view of the environmental burden of the treatment options under examination, this category is arguably the most crucial. The results of this LCA are intended for policy and decision makers, and GHG reductions currently serve as the backbone for many sustainability policy and targets in the EU. The Roadmap to a Low Carbon Economy, Renewable Energy Directive, and the Bioeconomy Strategy are climate policies and strategies that use GHG reductions as a measure of climate change mitigation and serve as a concrete indicator of progress. A critical assumption is made that only combustion of fossil carbon in waste or methanol results in emissions that contribute towards the GWP, and any carbon of biogenic origin is carbon neutral.

The time period considered is 100 years, as it is widely used among notable organization such as the Intergovernmental Panel on Climate Change. This long period also reflects that climate change is considered to be a problem for at least the next 100 years (ILCD, 2010). Weighting is not necessary for the impact assessment as only one impact category is utilized. Normalization is also not necessary because the goal of the LCA is to compare the products to each other rather than putting them in context of GWP per capita or other such comparison. Performing an LCA is an iterative process, thus the initial results are interpreted, and the entire process is reiterated as necessary. The final results are evaluated for completeness, sensitivity, and consistency. The limitations, sensitivity, and uncertainty within this research will be further discussed in a later section.

5. Results

5.1 Waste Treatments in 2020

Incineration-to-Energy

For incineration of RDF, the largest GHG emissions are the direct emissions of flue gases resulting from the combustion of the waste. Since the RDF in this LCA is considered to have a carbon content of 33.5%, and all carbon is assumed to be emitted as CO_2, this corresponds to 1.23 tons of CO_2 contained in 1 ton of RDF. Assuming 39% is of fossil origin, this results in direct emissions of 478 kg of CO_2/t RDF. There are also N_2O emissions that still remain in the flue gases after cleaning which amount to 12.7 $kgCO_2eq$/t RDF. The resulting total direct emission is thus 491 $kgCO_2eq$/t RDF, as shown by the dark blue segment in Figure 11. The chemicals used in this flue gas cleaning are the next most significant contributor to GWP; they amount to 7.24 $kgCO_2eq$/t RDF but are still nearly negligible. As is evident in Figure 11, the other processes and materials for incineration, such as wastewater treatment and the construction of the incineration facility, are also negligible in comparison to the direct emissions. The sum of all life cycle processes is 523 $kgCO_2eq$/t RDF. The biogenic emissions (green segment) are much larger at 751 $kgCO_2eq$/t RDF but are shown solely for demonstrative purposes and are not included in the life cycle emissions. If an LCA methodology were to choose to include these in the LCA, it is clear the large impacts this would have on the results.

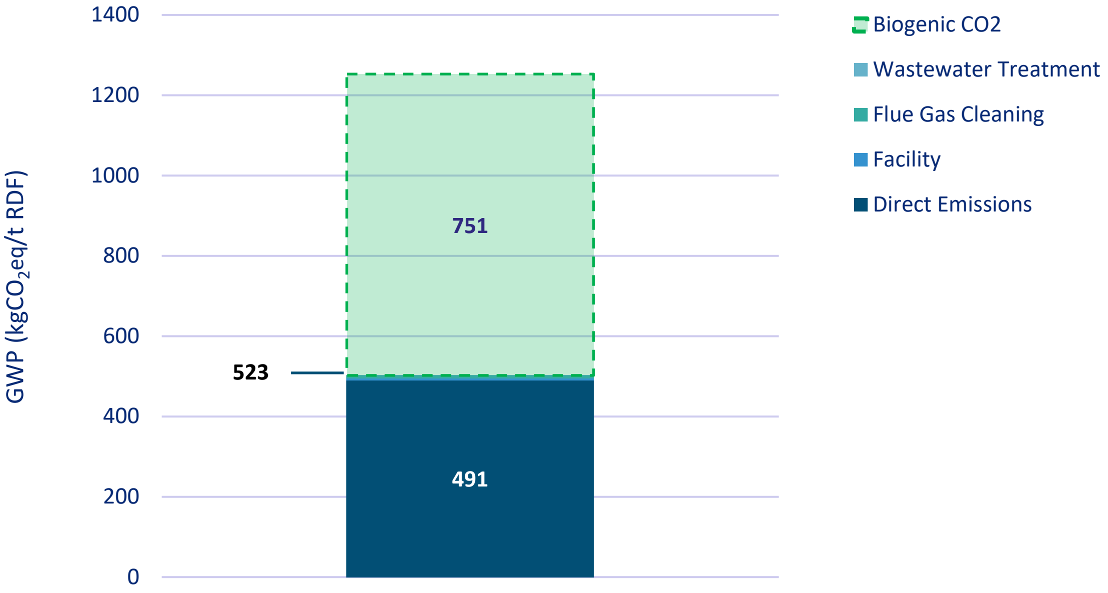


Figure 11. Global warming potential of emissions from energy (heat and electricity) resulting from the incineration of 1 ton of RDF. Direct emissions (dark blue) refers to fossil CO_2 and N_2O emitted and biogenic emissions (dotted green) refers to emissions of the biogenic fraction of RDF.

Gasification-to-Energy

The gasification of 1 ton of RDF for energy results in the same direct CO_2 emissions as incineration but has slightly lower N_2O emissions of 2.5 $kgCO_2eq$/t RDF. This results in lower direct emissions of only 480 $kgCO_2eq$ (dark blue), as seen in Figure 12. The lower N_2O emissions can be explained by the advantage of gasification to clean gases pre-combustion opposed to post-combustion. Though, gasification does have slightly higher emissions of 11 $kgCO_2eq$/t RDF associated with flue gas cleaning because of the sodium carbonate used to neutralize the acid gases and the activated carbon that binds heavy metals, dioxins and furans. Again, flue gas cleaning and other processes are nearly negligible when compared to direct emissions. The largest GWP contributor after direct emissions is auxiliary energy use, as the gasification plant requires the use of natural gas for startup of the gasifier and as backup which amounts to 37 $kgCO_2eq$/t RDF. The total GWP is thus 570 $kgCO_2eq$/t RDF which is approximately 9% greater than incineration. Since the RDF contains the same biogenic fraction as for incineration, the biogenic emissions are also 751 $kgCO_2eq$/t RDF, but again are considered carbon neutral.

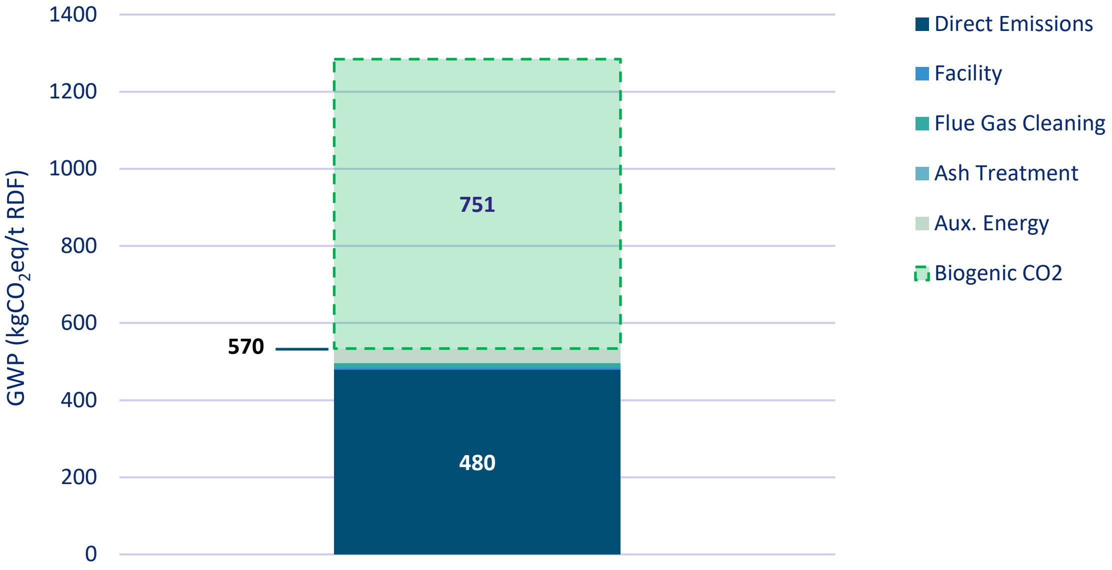


Figure 12. Global warming potential of emissions from energy (heat and electricity) resulting from the gasification of 1 ton of RDF. Direct emissions (dark blue) refers to fossil CO_2 and N_2O emitted and biogenic emissions (dashed green) refers to emissions of the biogenic fraction of RDF.

Gasification-to-Methanol

For the production phase of gasification-to-methanol, the direct emissions to air are only 226 kgCO$_2$eq/t RDF compared to the 480 kgCO$_2$eq/t RDF of gasification-to-energy production. This is because 53% of the carbon contained in the RDF is embedded in the methanol, and only the remaining 47% of the carbon is emitted as CO$_2$ during the production phase, of only which 39% is fossil based. Similar to gasification-to-energy, methanol production also requires auxiliary energy for which natural gas is used. One of the few differences is that the methanol synthesis step requires metal oxide catalysts to convert syngas to methanol, but only results in emissions of 2 kgCO$_2$eq/t RDF. The total emissions of the production phase are 280 kgCO$_2$eq/t RDF, but when also considering the use phase, the 254 kgCO$_2$eq/t RDF that was embedded in the methanol is released as CO$_2$, resulting in a total GWP of 533 kgCO$_2$eq/t RDF. The two green segments in Figure 13 indicate the biogenic emissions from the production and use phase. Again, these are not included in the LCA as they are considered carbon neutral but are shown for demonstrative purposes.

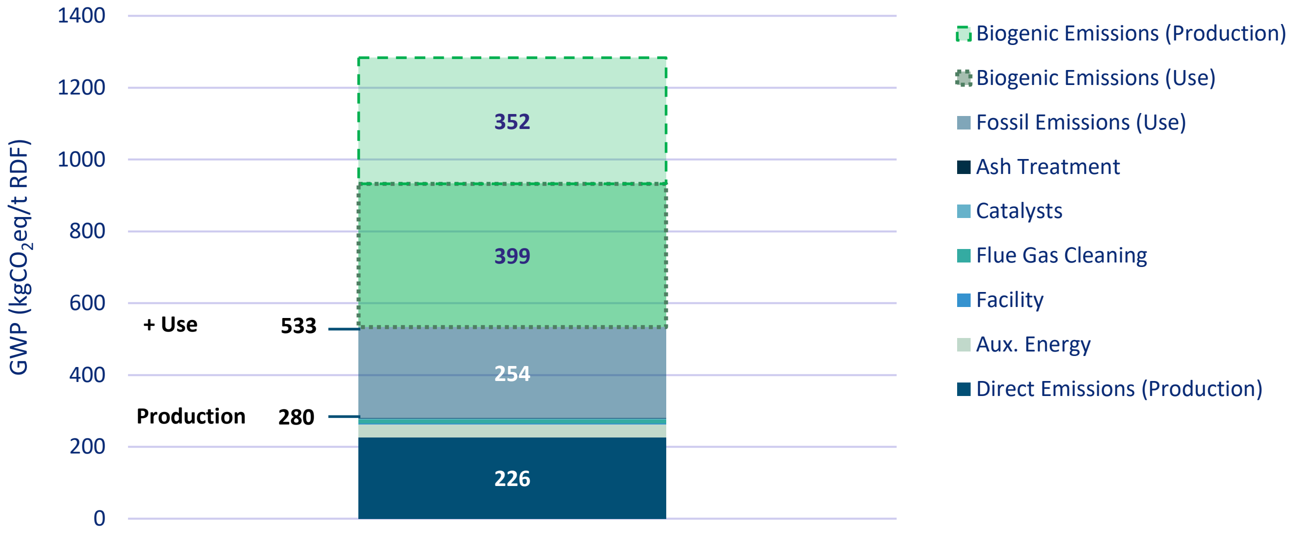


Figure 13. Global warming potential of emissions resulting from the gasification of 1 ton of RDF and production of methanol. Fossil emission of production and use phase are shown in dark and light blue and for biogenic emissions are shown in light and dark green.

Comparison of Waste Treatments

In Figure 14, the GWP of three waste treatments in 2020 are compared to the reference products of that year (solid bars versus dotted bars) in terms of $kgCO_2eq/t$ RDFeq. The unit ton RDFeq refers to the amount of energy or methanol produced from 1 ton of RDF and translates to the amount of reference energy or methanol it is compared to. Figure 14 shows that when *only* the production phase is considered for each waste treatment, gasification-to-energy has the largest net reduction in GWP of 405 $kgCO_2eq/t$ RDFeq when compared to the reference product (solid dark blue bars compared to dotted dark blue bars). Despite the emissions associated with the production being the highest of all waste treatment options, the burdens from the reference heat and electricity generated are also the greatest. This is largely due to the electrical and heat efficiency of gasification is 74.8% in this year compared to the 42% efficiency of the incineration plant. Once the use phase is included, however, it is rather gasification-to-methanol that results in the largest reduction in GWP compared to the reference, in both absolute and relative terms. It has a net GWP reduction of 484 $kgCO_2eq$, corresponding to a 48% decrease in GWP of the reference methanol. When only the production phase is considered, RDF derived methanol has a slightly lower GWP than the reference methanol, of 280 versus 365 $kgCO_2eq/t$ RDFeq. Yet, once the use phase is accounted for in the life cycle there is a large reduction of 484 $kgCO_2eq/t$ RDFeq. The reason is that RDF is only 39% fossil based whereas methanol from natural gas is entirely fossil based. Thus, when the use phase is included, in this case combustion, the methanol from RDF emits nearly two thirds less GHGs than methanol from natural gas because it is partially biogenic and is considered carbon neutral.

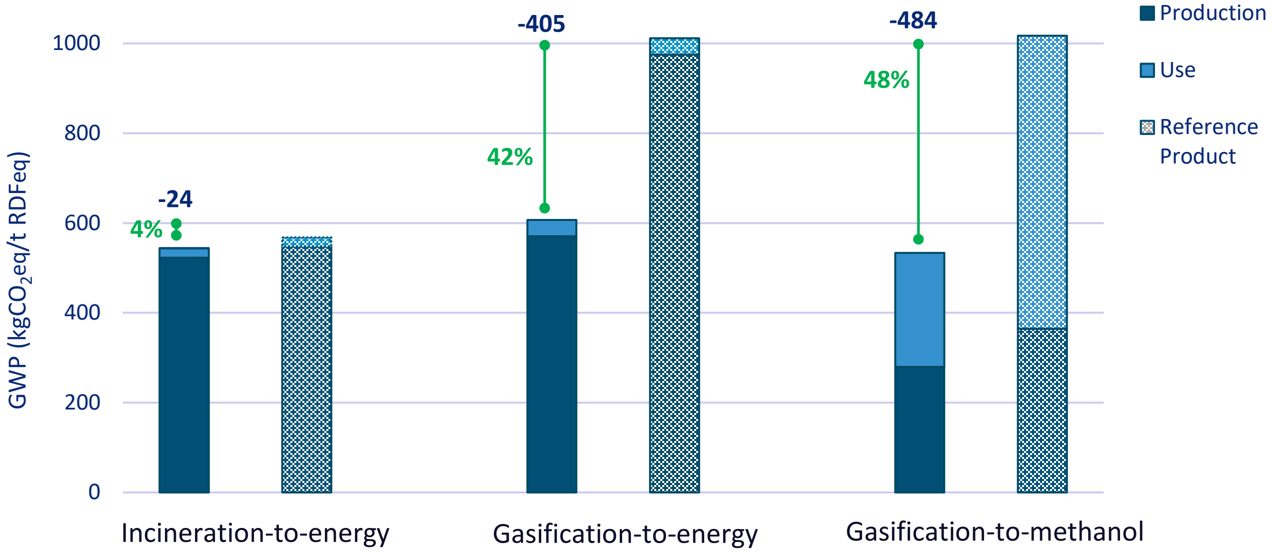


Figure 14. GWP of RDF derived energy and methanol (solid bars) compared to reference products (dotted bars) for different waste treatment options in 2020. Green bars indicate net reduction of GWP compared to reference in absolute and relative (%) terms.

By not including the use phase, this inherently biases the WtM LCA results in a negative manner. This is because for WtE applications, the majority of emissions occur in the production phase when the energy is produced, and very few are emitted during the use phase which only involves the transmission and distribution of the energy. The reductions when compared to the reference heat and electricity are thus already apparent in the production phase. Contrarily, for WtM the reduction compared to the reference product is not apparent until the use phase is included. This is because the reduction in emissions for RDF derived products compared to the reference products stem from RDF containing only 39% fossil-based carbon and the reference products in 2020 being entirely fossil based. Approximately half of the carbon from these feedstocks is embedded in methanol, so the reductions are not observed until the combustion of the methanol is included, when this embedded carbon is then released as CO_2. This demonstrates that only considering the production phase does not provide a fair comparison between energy and chemical products. Thus, the remainder of the LCA results will include both the use and production phases to fairly compare the two.

5.2 Waste Treatments in 2030

Comparison of Waste Treatments and Scenarios

As seen in Figure 15, in 2030 both gasification treatments result in a net reduction in GWP compared to the reference product, regardless of the scenario. The largest difference between scenarios is observed for gasification-to-methanol with a net reduction of 577 kgCO$_2$eq/t RDFeq in the BAU Scenario and only 407 kgCO$_2$eq/t RDFeq for the Breakthrough Scenario. This is because the reference methanol in the BAU Scenario is far more carbon intensive, both in the production and use phase, and results in a larger avoidance of emissions.

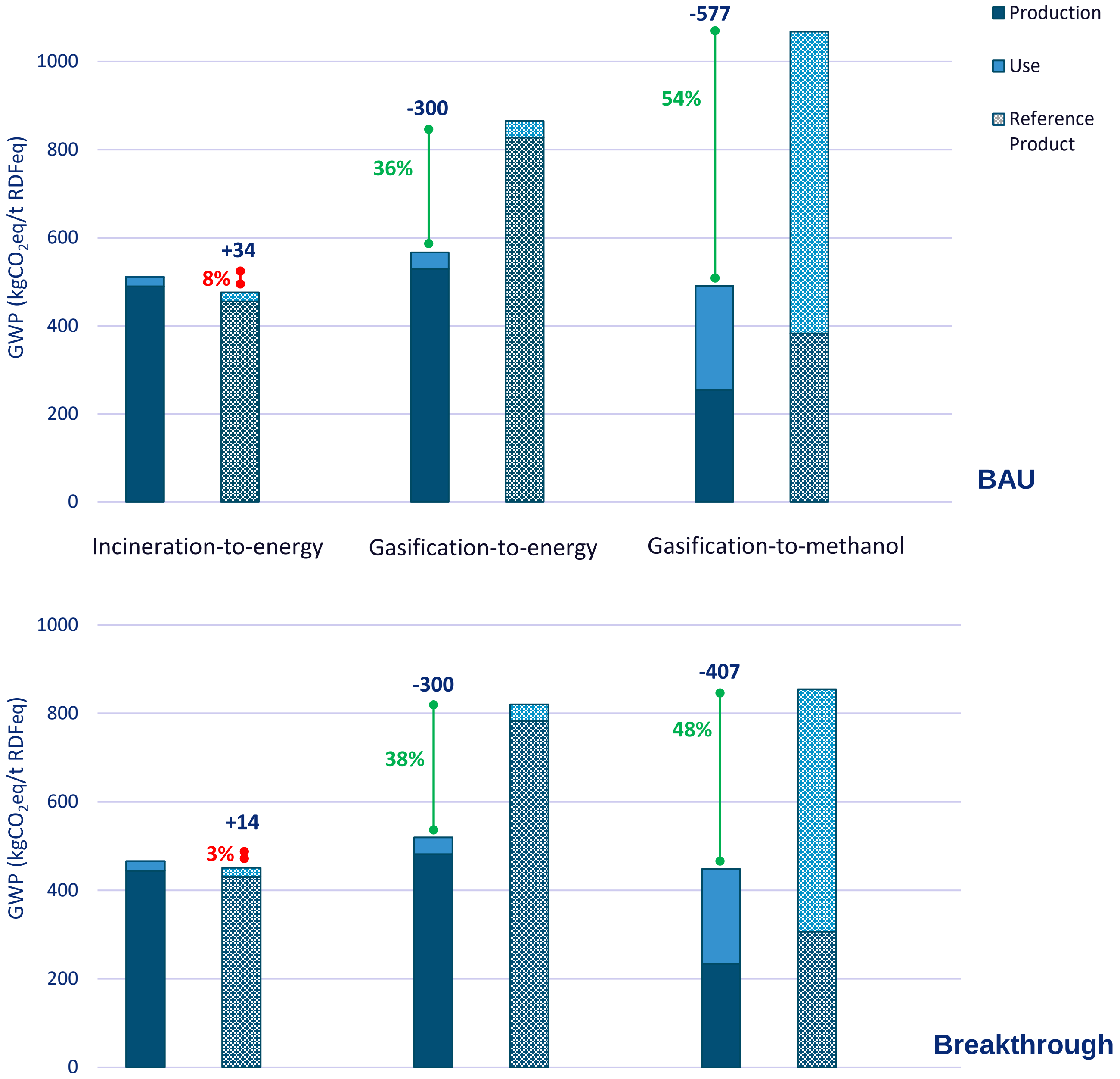


Figure 15. GWP of RDF derived energy and methanol (solid bars) compared to reference products (dotted bars) for different waste treatment options in 2030 for the BAU (top) and Breakthrough (bottom) Scenarios. Green and red bars indicate net reduction or increase of GWP compared to reference product in absolute and relative (%) terms.

The reference methanol in the BAU Scenario is assumed to be 100% natural gas based whereas the Breakthrough Scenario assumes a 20% reduction in the GHG intensity of methanol in 2020, presumed to be due to the increase of biomass, specifically wood chips, as a feedstock. Thus, a fraction of the emissions for the reference methanol in the Breakthrough Scenario, both in the production and use phases, are considered biogenic and carbon neutral. Even though the GWP of the production phase of methanol from RDF is lower in the Breakthrough Scenario because the RDF is assumed to be slightly more biogenic in this scenario (67% compared to 64% in the BAU Scenario), the larger emissions of the reference methanol in the BAU Scenario outweigh this phenomenon.

For gasification-to-energy, the BAU and Breakthrough Scenarios result in very similar net GWP reductions of 300 $kgCO_2eq/t$ RDFeq. However, it must be noted that this is coincidental, and these scenarios do not have identical underlying processes. The gasification of RDF in the BAU Scenario is more GHG intensive than in the Breakthrough Scenario (529 vs. 482 $kgCO_2eq/t$ RDFeq) because of the higher fossil content of the RDF. This is compensated by the reference energy being more GHG intensive in the BAU Scenario and resulting in larger emissions of 827 $kgCO_2eq/t$ RDFeq compared to 782 $kgCO_2eq/t$ RDFeq in the Breakthrough Scenario. The difference between the RDF derived energy and the reference energy consequently results in a net GWP of 300 $kgCO_2eq/t$ RDFeq for both scenarios.

The most notable feature of Figure 15 is the increase in net GWP for incineration in both scenarios. This is because heat and electricity have decarbonized since 2020 and the reference energy emissions thus become smaller. The BAU Scenario in this case leads to a larger net increase of GWP because the reference electricity is assumed to be less GHG intensive than the Breakthrough Scenario, and results in lower emissions. The net GWP increases for the BAU and Breakthrough Scenarios are fairly small at 34 and 14 $kgCO_2eq/t$ RDFeq, equivalent to an increase of 8 and 3% of the reference energy. These emissions could be within the limits of the margin of error and it cannot be said with certainty that incineration leads to a net increase or decrease in GWP. Nonetheless, incineration is clearly the least desirable waste treatment option when compared to gasification, even considering the uncertainty of these values.

5.3 Waste Treatments in 2050

Comparison of Waste Treatments and Scenarios

In 2050, incineration remains as an unfavorable option for waste treatment as it results in a net increase in GWP compared the reference energy being provided by the heat and electricity grids. This is true for both scenarios, however the BAU Scenario results in a much larger increase of 203 kgCO$_2$eq/t RDFeq, or 91% more emissions compared to the reference energy. Although this scenario has greater emissions of the reference energy because it assumes less ambitious achievements in renewable energy from the grid, the RDF treated is assumed to have a greater fossil fraction because of slower substitution of fossil-based materials for biobased ones.

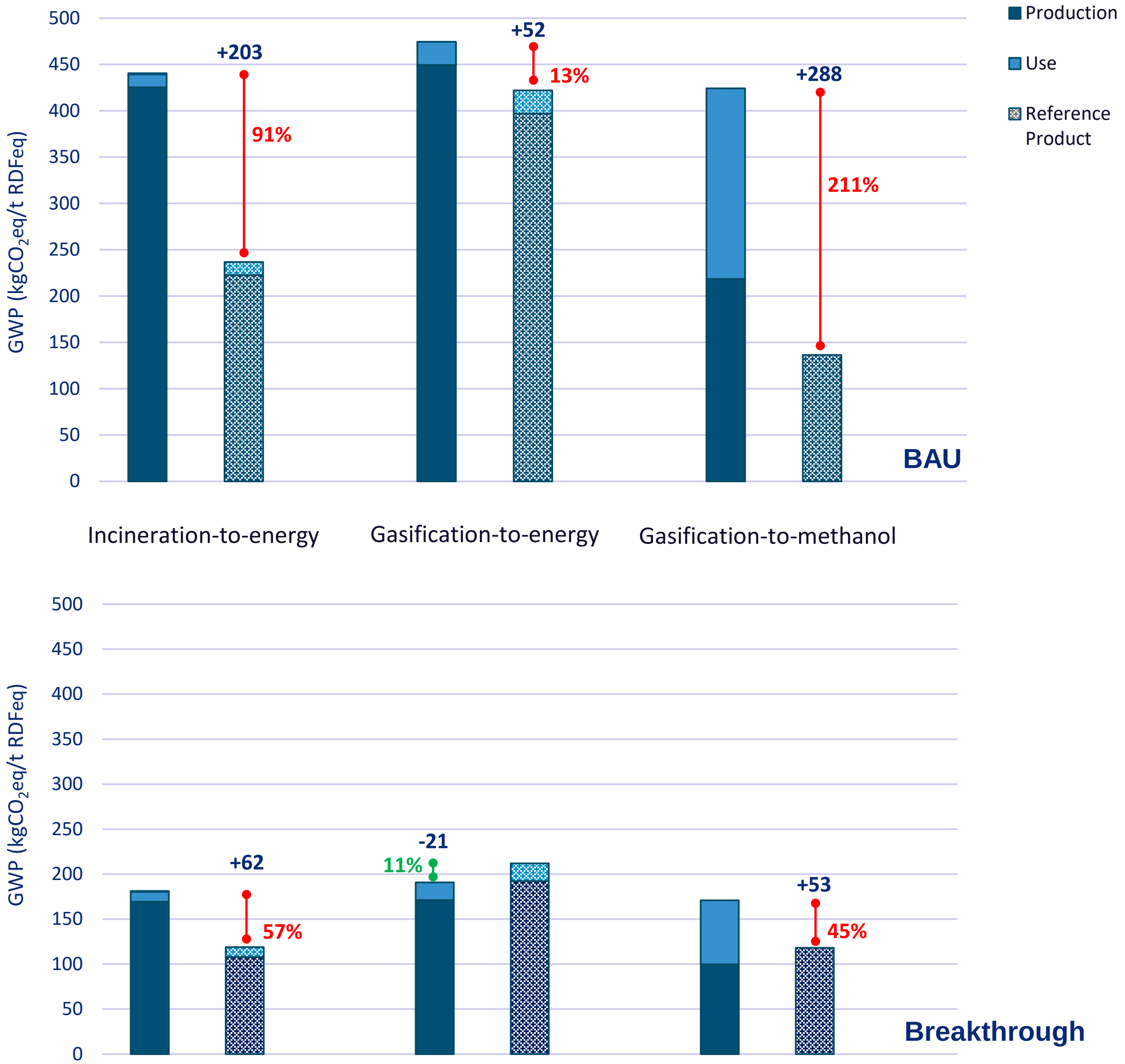


Figure 16. GWP of energy and methanol from RDF (solid bars) compared to reference products (dotted bars) for different waste treatment options in 2050 for the BAU (top) and Breakthrough (bottom) Scenarios. Green and red bars indicate net reduction or increase of GWP compared to reference product in absolute and relative (%) terms.

For gasification-to-energy, the BAU and Breakthrough Scenario result in opposite conclusions; the BAU Scenario demonstrates a net increase in GWP of 52 $kgCO_2eq$/t RDFeq whereas the Breakthrough Scenario results in a small reduction of 21 $kgCO_2eq$/t RDFeq. The BAU Scenario does have greater reference emissions because of the greater GHG intensity of the reference energy, but this is overcome by the larger emissions produced by energy from RDF. The energy from the gasification of RDF is more GHG intensive than the grid because this scenario assumes a 32% fossil fraction of the RDF whereas the reference heat and electricity contain much lower shares of fossil feedstocks. As for the Breakthrough Scenario, the energy from gasified RDF is slightly less GHG intensive than the grid, largely due to the fact that this scenario assumes only 11% of RDF being fossil-based. As in 2030, the uncertainty and margin of error of these values must be considered. The relative differences between the RDF derived energy and reference are 13% and 11% for the scenarios, and if the margin of error is greater than this, then no difference between the products can be claimed.

Methanol production highly varies between scenarios in 2050, with the BAU Scenario resulting in a net increase of 288 $kgCO_2eq$/t RDFeq and 53 $kgCO_2eq$/t RDFeq for the Breakthrough Scenario in absolute terms. In relative terms the RDF derived methanol in the BAU Scenario is 211% greater than the reference methanol, and only 45% for the Breakthrough Scenario. This disparity arises from the difference in GWP of methanol from RDF and less so from the difference in GWP of the reference methanols. The BAU Scenario assumes 100% biomass for the reference methanol and in the Breakthrough Scenario it is assumed to be from CCU; the life cycle GHG intensities of these are similar, at 0.261 vs. 0.226 $kgCO_2eq$/kg methanol. The large difference between scenarios is rather that the fossil fraction of RDF in the BAU Scenario is 32% compared to only 11% in the Breakthrough Scenario. The emissions from the production and use phases of methanol from RDF in the BAU Scenario are consequently much higher than in the Breakthrough Scenario, at 424 versus 171 $kgCO_2eq$/t RDFeq. In summary, of the waste treatment options considered in 2050, gasification-to-energy is the best option in both scenarios, as methanol has largely decarbonized, and energy has not to the same extent.

Effect of Reference Methanol

As is evident most prominently in the 2050 scenarios, the choice of reference methanol has a large effect on the resulting GWP calculated in this study. The life cycle emissions of methanol can highly vary depending on the feedstock utilized or methodology used, such as allocation methods or what it is included within the boundaries of the LCA. Variations occur not only in the production phase, but also in the use phase. The GWP of methanol from natural gas versus wood chips differs more than 5-fold when considering both the production and use phases, as shown in Figure 17. If only the production phase were considered, methanol from RDF in the BAU Scenario would have a lower GWP than methanol from short rotation coppice. Once the use phase is included though, the use phase for short rotation coppice has no fossil emissions and the methanol from RDF is 32% fossil-based. This results in overall higher emissions with a GWP of 0.811 kgCO_2eq/kg methanol. When the use phase is included, all types of biomethanol perform better on a GHG basis than the RDF-based methanol in this scenario. It is only in the Breakthrough Scenario in which RDF is only 11% fossil based that RDF-based methanol can compete with biomethanol on a GHG basis. It is less GHG intensive than methanol from short rotation coppice and wood residues and has the same intensity as biomethanol from wood chips from the Ecoinvent database. The LCA from the database, however, assumes current biomethanol processes which uses partially fossil-based electricity. If the electricity use in production is changed to reflect the renewable electricity generation in 2050 in this scenario, the adjusted GWP would be approximately 0.261 kgCO_2eq/kg methanol, outperforming the RDF based methanol in the Breakthrough Scenario which has a GWP of 0.327 kgCO_2eq/kg methanol.

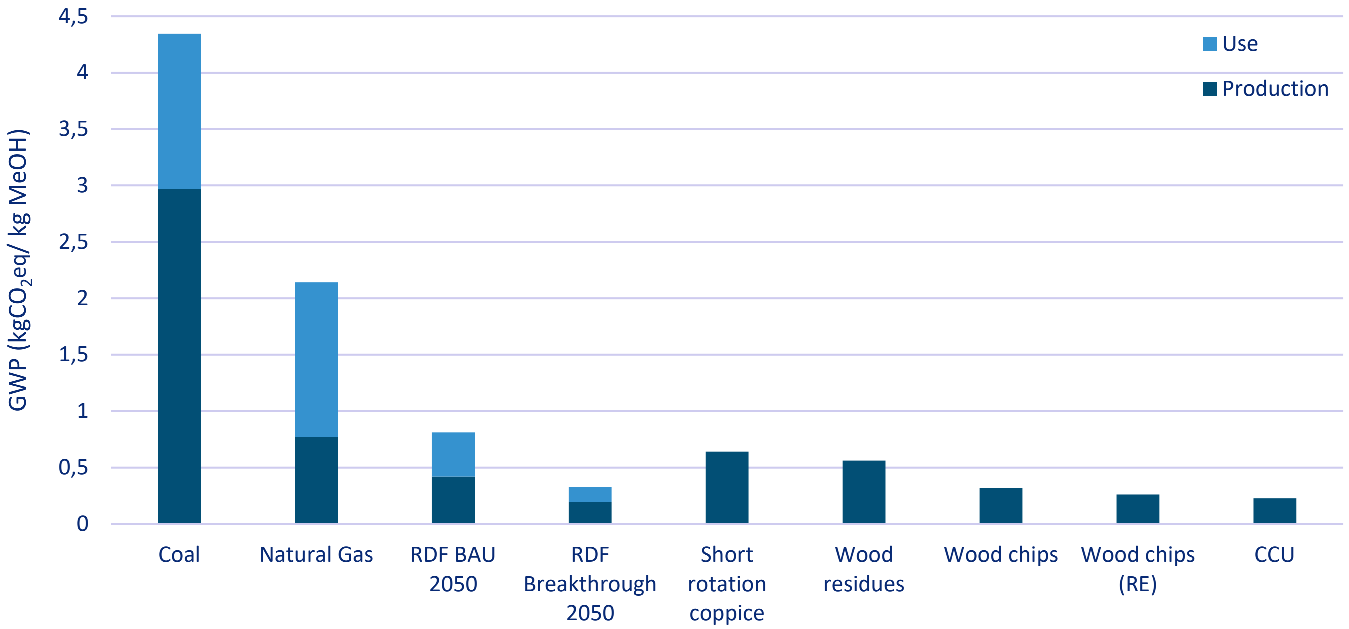


Figure 17. GWP of the production and use phase of methanol from different feedstocks.

The CCU methanol has the lowest GWP of all the methanol processes in Figure 17, at 0.226 kgCO_2eq/kg methanol. This is because like biobased methanol, it has sequestered industrial waste CO_2 as a feedstock and is consequently considered as carbon neutral when combusted. The production phase also has the lowest emissions compared to other biobased options (not including RDF). Although it is not entirely clear from the study, some of these emissions include electricity use. Since the electricity use in the Breakthrough 2050 Scenario is assumed to be nearly all renewable, the emissions would be even lower than estimated in the study.

5.4 Timeline of Waste Treatments

As one looks at the timeline of the evolution of waste treatment, as exhibited in Figure 18, for both scenarios there is a general trend of each waste treatment option resulting in a less favorable net GWP over the decades. The only exception to this trend is gasification-to-methanol in the BAU Scenario, where a decrease in GWP is observed from 2020 to 2030. This is because the reference methanol (100% natural gas based) remains the same across this decade while the RDF becomes slightly more biogenic in this same period.

Figure 18. Net GWP (RDF product compared to reference product) of each waste treatment from 2020 to 2050 including production and use phase of the BAU Scenario (top) and Breakthrough Scenario (bottom). The star indicates the most favorable waste treatment option for that year.

For the remainder of circumstances, electricity and heat become less GHG intensive over time as renewables expand and replace fossil fuels in both the BAU and Breakthrough Scenarios. The same is observed for methanol, and over the decades the reference methanol becomes increasingly less GHG intensive due to the increased use of biomass and decreased use of natural gas as a feedstock. Essentially, the reference products are able to decarbonize at a faster rate than the RDF derived products which results in RDF recovery to be less and less appealing over time in terms of climate change mitigation. The limiting factor for decarbonizing RDF derived products is that the RDF is partially fossil based in every decade, and by 2050 it can simply not compete with reference products that replace their fossil feedstocks at a quicker rate. Even in the Breakthrough Scenario in 2050 which assumes a 72% replacement rate of fossil-based RDF with biobased materials, the net reductions of GWP for methanol production become much smaller from 2030 to 2050.

Tipping Points

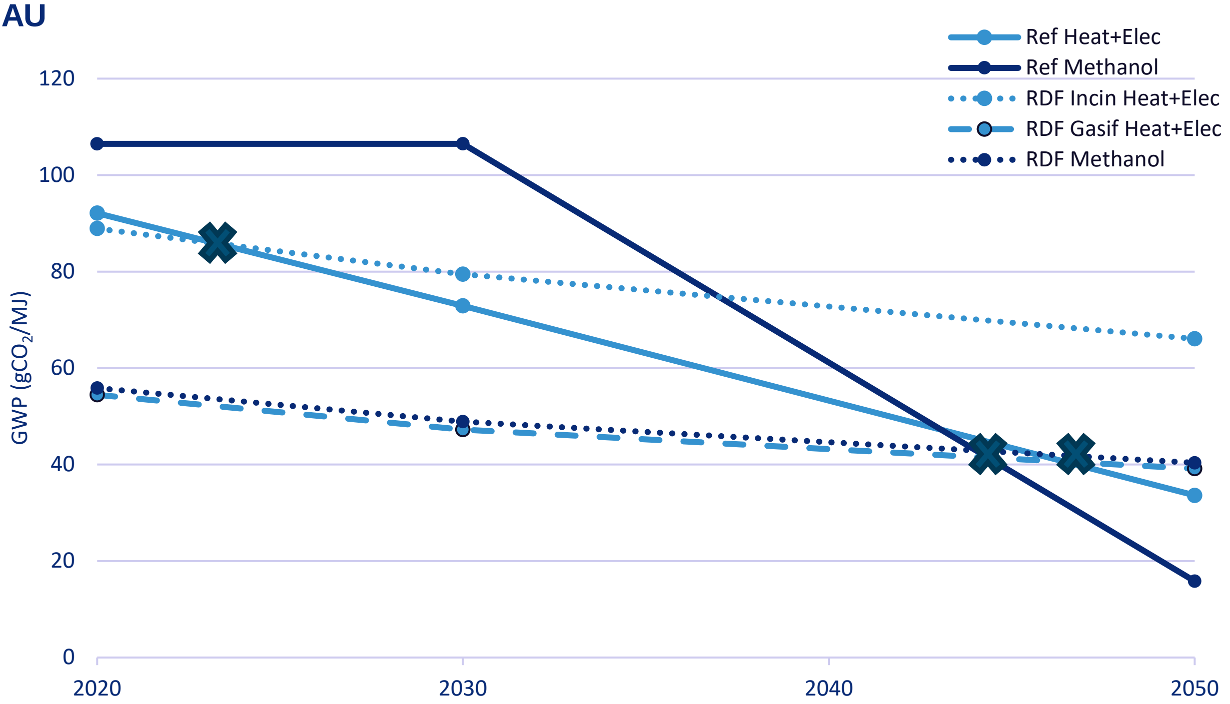
For each year a tipping point can be determined for each waste treatment technology which can be described as the GHG intensity of the life cycle of the reference product at which the treatment of waste would have a neutral GWP. If the life cycle of a reference product has a GHG intensity above this tipping point, then it would result in a net increase in emissions. Alternatively, any value lower would result in a net reduction of GWP. This tipping point cannot of course represent the exact GHG intensity of the reference electricity, heat, or methanol that results in carbon neutrality because this aLCA did not consider marginal technologies or indirect effects of the waste technologies. However, it still serves as an informative estimation or benchmark for considering which waste treatment is optimal in which reference circumstance. The GHG intensities of the RDF based products, the dashed lines in Figure 19, are expressed as gCO_2 per MJ generated per ton of RDF. This means that these tipping points assume the electricity, heat, and methanol production efficiencies for 1 ton of RDF treatment of that year and cannot be accurately used outside of this context.

It is evident from Figure 19 that incineration is the easiest for alternatives to compete with, as the reference product lines (solid lines) fall below incineration the earliest. If there was a linear change in GWP of each product from decade to decade (which is not the case), the tipping point would be where a dotted line of one product crosses the solid line of the respective reference product, as indicated with an x in Figure 19. In the BAU Scenario, for incineration this would occur somewhere between 2020 and 2030 and for gasification it would not be until some point between 2030 and 2050. This is because of the significantly higher efficiency of gasification than incineration which results in a significantly lower GWP per unit of energy. This also implies that gasification is likely to be viable from a GHG perspective longer term than incineration. With all three tipping points being reached by 2050, this demonstrates that the decarbonization rates of the references are faster than that of the RDF technologies within this 30-year period.

In the Breakthrough Scenario, the tipping point for incineration of RDF also occurs at a point between 2020 and 2030. For gasification-to-methanol the tipping point is much later, nearer to 2050. Although the tipping point for gasification-to-energy is not reached by 2050, it is on the verge, so would most likely occur soon after 2050. Only two of the three tipping points are reached in this scenario because although it assumes ambitious decarbonization of the reference, the RDF gasification technologies also decarbonize. This can be largely attributed to the rapid increase of biobased materials in the RDF. Direct emissions from the RDF technologies that were previously fossil-based become increasingly biogenic, thus carbon neutral, and indirect emissions from auxiliary energy also decrease.

The tipping points are informative because they can provide a sense as to how long a waste treatment may be viable from a GWP perspective. They cannot provide an exact date, as one cannot assume a linear change from decade to decade. However, they can provide an estimation of the long-term viability of a technology when compared to different reference product developments. For example, it is clear from both scenarios that incineration will not remain viable from a climate change mitigation perspective long-term, as the tipping points are somewhere between 2020 and 2030. These tipping points do of course rely on the assumptions of how the references will develop but still serve as a useful benchmark. They can be used to test against certain assumptions made for a reference product or to compare between different assumptions or scenarios for future reference product developments.

BAU



Breakthrough

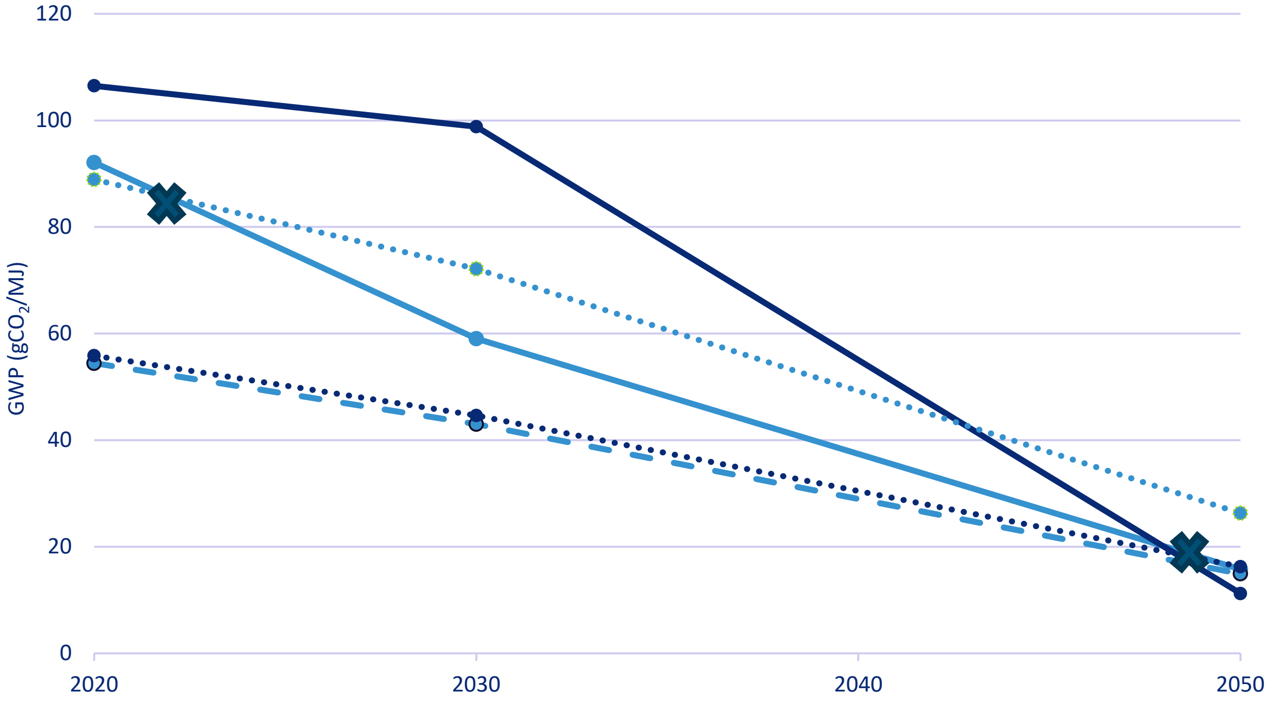


Figure 19. The GWP of RDF derived products versus reference products for 2030 to 2050 for the BAU Scenario (top) and Breakthrough Scenario (bottom). Tipping points of reference and RDF equivalents indicated with an x.

5.5 Sensitivity Analysis

The parameters that are most sensitive for each waste treatment LCA are the assumed characteristics of the RDF; every emission calculated, both biogenic and fossil, stem from these assumptions and can be greatly influenced by minor variations. The characteristics of greatest importance are the biogenic fraction, the LHV, and the carbon content. The biogenic fraction is extremely influential on every direct emission downstream of RDF, as biogenic waste is considered carbon neutral when combusted. This also relates to the carbon composition, as the amount of carbon dictates the stoichiometry, and thus potential CO_2 to be emitted from the combustion or gasification of RDF. The LHV of the waste is also a very sensitive parameter and although it does not greatly influence emissions associated with the production and use phase of waste treatment, it does have a larger effect on the emissions of the reference heat and electricity to which it is compared. Since the LHV is defined as the usable energy contained in the RDF, the higher the value, the greater amount of energy can be generated and displaced from the grid.

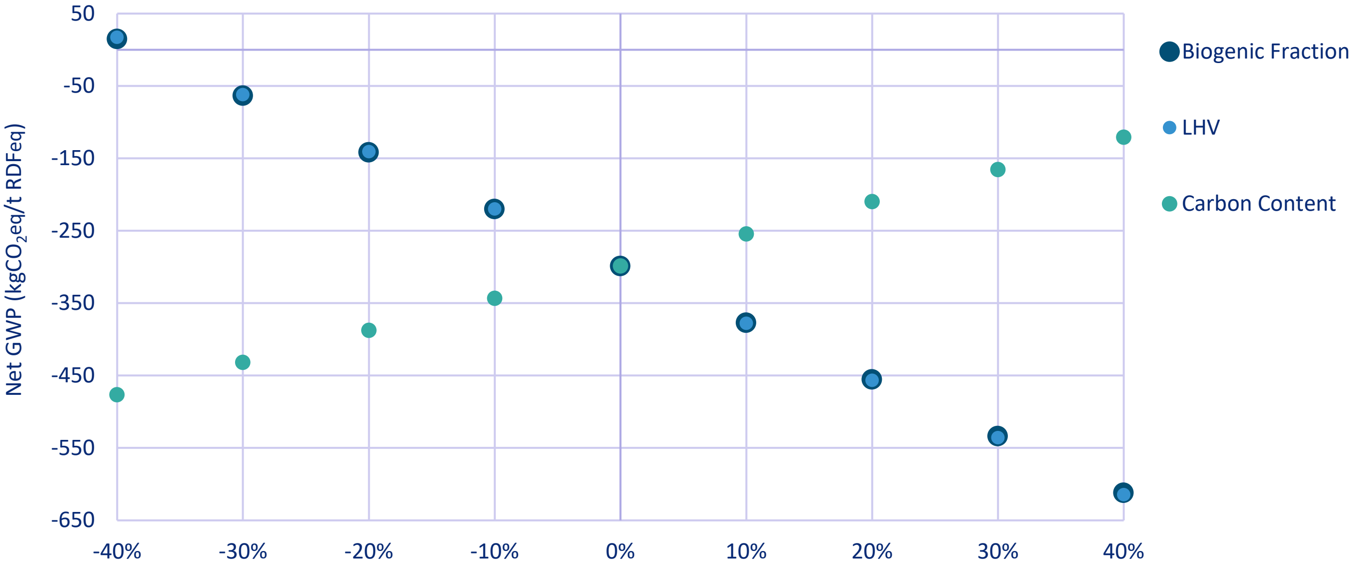


Figure 20. A sensitivity analysis of the effect of the biogenic fraction, LHV, and carbon content of the waste on net GWP of gasification-to-energy versus the reference energy for the BAU Scenario in 2030. The x-axis shows the percent change of these variables from the assumption made in this scenario.

Figure 20 displays a sample sensitivity analysis for the 2030 BAU gasification-to-energy LCA. It shows the effect of changing these variables, as a percent change from the assumption made in the study, on the net GWP of the RDF versus reference energy. All parameters affect net GWP in a linear fashion, although as the carbon content of the RDF increases the net GWP reduction increases and the inverse is observed for the biogenic fraction and LHV of the waste. These two variables affect net GWP in the same way because an increase in biogenic fraction lowers the GWP of the RDF based energy to the same degree as increasing the LHV, thus overall thermal efficiency of the energy, and emissions of the reference. As can be seen by the difference in slope of these lines, the net GWP is more sensitive to changes in the biogenic fraction and LHV than the carbon content. As MSW is a very heterogenous feedstock, these parameters can largely fluctuate depending on geography, the time of year it is collected, the waste separation system in place, and several other factors. Therefore, it is more important to acknowledge their level of sensitivity rather than trying to accurately predict the exact values.

6. Conclusions

The results of the LCAs can be interpreted and used to answer the main research question, *what is the optimal pathway for MSW treatment in terms of overall greenhouse gas emissions and resulting climate change mitigation in the Netherlands in 2020, 2030, and 2050*? The comparative LCAs performed for 2020 conclude that if natural gas is indeed the reference feedstock for methanol production, then gasification-to-methanol results in the largest reductions in GWP and would be the optimal way to handle MSW. The LCA results for incineration in this year show that this is the least preferable way to treat waste from a GWP perspective, considering the efficiency is significantly lower than gasification. These conclusions for 2020 are the most certain, as this is the nearest time horizon studied.

In 2030, the conclusions of the LCAs remain largely the same. If either the BAU Scenario or Breakthrough Scenario were to unfold, then gasification-to-methanol rather than gasification-to-energy is still the optimal way to treat waste. This is because methanol decarbonizes at a slower rate than power and heat, for which there are already many cost-effective alternatives by 2030. Nevertheless, gasification-to-energy remains the better of the WtE options and results in net reductions in GWP compared to the reference in both scenarios. Incineration remains as the least favorable option and by 2030 it has surpassed the tipping point and results in slight net increases of GWP compared to the references.

The year 2050 presents substantially different conclusions compared to previous decades. In a plausible future in 2050, all waste treatments result in a net increase in GWP compared to the references. This implies that none of these are logical from a GHG perspective, as they are producing greyer products than the ones they replace. The best, or better described as the least worst option in this scenario, is gasification-to-energy rather than methanol, contrary to previous decades. This can be explained by the reference methanol being entirely biobased, resulting in very few avoided emissions. The Breakthrough Scenario in 2050 illustrates a different outcome, in which gasification-to-energy results in a slight net GWP reduction. This is due to the assumption that RDF has increased its biogenic fraction to 89% in this scenario, and consequently decarbonizes faster than energy was able to in these two decades. The reference methanol however decarbonizes to a large degree because of CCU technology and has reached the tipping point by 2050.

Considering these results, it is recommended that the Netherlands should transition from the incineration to gasification of waste. Since gasification has comparable emissions to incineration, but a greater thermal efficiency, it replaces a larger amount of electricity and heat from the grid in the case of energy production. As long as RDF gasification produces cleaner energy than the grid, it is beneficial from a climate change perspective. In the near term however, syngas should be upgraded to methanol rather than combusted for energy as methanol is likely to decarbonize at a slower rate than energy in both a BAU and ambitious future. Gasification-to-methanol could thus mitigate climate change to a greater degree. By 2050, only in an ambitious future will gasification-to-energy be beneficial from a GWP perspective, and even this conclusion is not within a range of certainty. Waste gasification will no longer be beneficial for climate change mitigation by 2050 because both energy and methanol will be heavily decarbonized. This implies that waste solutions other than the ones investigated should be explored, as they may no longer be beneficial for climate change mitigation past 2050. Policy and research should instead focus on higher levels of the waste hierarchy such as reduction, re-use, and recycling. If there is still waste remaining at the recovery level, other end products that are tougher to decarbonize should be prioritized if possible.

These recommendations are made from direct interpretations of this study’s results, yet this research can only capture a small part of the entire waste management landscape. They should thus be critically assessed and tested within other contexts. The next section will discuss some additional factors to consider when interpreting the results and will also address the limitations of this research.

7. Discussion

7.1 Lock-In Effect

The conclusions offer recommendations as to how waste should be treated in the Netherlands to mitigate climate change. However, there are more factors than climate change mitigation that are taken into consideration when investing in and developing waste treatment technologies and infrastructure; therefore, the results of the LCA need to be considered within a larger context. In the Netherlands specifically, incineration infrastructure has already been heavily developed and large investments in plants have been made. This creates a certain lock-in effect, as the lifetime of a plant is 25 years on average. Switching to a new technology before the end-of-life of these plants would therefore result in stranded assets and would not be economically beneficial. For example, the most recent plant at AEB was constructed in 2007 and it is likely that it will be operating in 2020 and perhaps even 2030. Although the results of this study suggest it may be more beneficial for climate change mitigation to retrofit such a plant to a gasification-to-methanol plant, there is currently little economic incentive to do so. There is the added difficulty of overcoming the technological hurdles of gasifying biomass, which can prove to be a difficult feedstock to handle compared to fossil fuels. Most experience with gasification thus far has been with fossil fuels such as coal, and biomass presents new technological challenges such as tar formation and logistical challenges of developing new and sustainable supply chains. These factors hinder the adoption of gasification in the Netherlands up to 2030, but do not render it impossible to implement in other countries that have not yet heavily invested in waste infrastructure.

This study focused on the Netherlands specifically, but the results can be translated to other countries to some degree. Regardless of the reference energy or methanol within a country, it was shown that gasification provides higher energy efficiency than incineration, thus greater GHG emission reductions. This means that countries who have not yet invested in either technology are advised to build gasifiers if they wish to reduce their GHG emissions. The LCA for 2020 is also relevant to most other EU Member States as it assumed the reference methanol to be produced from natural gas, and this is the common practice for most of Europe. Thus, if the composition of waste treated is similar to the Netherlands, gasification-to-methanol would also be the ideal way for these countries to treat waste. The GHG intensity of energy, however, differs more vastly across countries than for methanol, so recommendations for waste treatment could differ. For example, gasification-to-methanol rather than gasification-to-energy is the optimal choice in 2020 and 2030 for both scenarios in the Netherlands, largely due to the energy mix decarbonizing faster than the RDF treatments and leading to less emissions. For a country with very GHG intensive electricity and heat, such as Poland who heavily relies on coal, gasification-to-energy and even incineration may be most viable from a GHG perspective, as the energy being displaced is more GHG intensive than for methanol. It is clear the decarbonization rates of methanol and energy within a country will heavily determine the option that is most viable for global warming mitigation. Since the calculations for the RDF LCA have already been made, these can be used to compare to the reference energy and methanol of any country. So, although the results may not all be applicable beyond the Netherlands, the methodology can be quickly adopted and translated to any country who seeks to assess waste treatment options.

7.2 Future Waste Composition

The results of the sensitivity analysis show that a very influential factor for the life cycle performance of each technology is the biogenic fraction of the RDF. It can heavily dictate whether a certain waste treatment will negatively affect global warming. The difficulty is that unlike conventional energy or methanol feedstocks, RDF is generated rather than deliberately sourced, thus the biogenic composition cannot be *directly* controlled. However, there are *indirect* ways to control the output of waste by dictating the composition of the original input. In the case of RDF, the fossil fraction consists mostly of non-recyclable plastics, due to the original input of fossil-based plastics. Thus, it is both the development of plastic production and plastic recycling technologies that could potentially influence this fossil fraction and overall composition most in the future. Current EU policies are implemented to increase recycling rates of MSW, so it is foreseeable that the amount of fossil-based plastics in RDF will decline in the future. These recycling rates could increase by either expanding the use of current technologies or innovating and developing new ones. RDF is currently defined as the “non-recyclable” material from waste, but every material is recyclable in theory. A material that is currently categorized as non-recyclable may be recyclable in 2050 as recycling technologies advance and more attention is put towards material scarcity. Although this would help waste treatment climb a level higher in the waste hierarchy from recovery to recycling, this could concomitantly decrease the efficiency of waste that can only still be treated for recovery. Removing non-recyclable plastic from RDF would lower the fossil fraction, but would concurrently lower the LHV of the waste, as plastics are the fraction with the highest LHV and energy potential. This would be detrimental to the energy efficiencies of both incineration and gasification and could result in these technologies no longer being viable from a GHG or even economic perspective. Though, it could be overcome if fossil-based plastics were replaced with biobased ones, as they could maintain a high LHV of the waste treated but would be considered biogenic when combusted.

The growth of such biobased materials is expected in the Netherlands, and several Dutch companies who are global players in the chemical sector, such as Shell, DSM, and AkzoNobel, are already investigating biobased alternatives for current petroleum-based products (Ministry of Economic Affairs, 2013). It is however not only uncertain to what degree this growth will be, but also which biobased materials will influence the composition of RDF. Much of the expected growth in biobased materials is specifically for biodegradable polymers. Often confused with *biobased* polymers*, biodegradable* polymers can be either bio or fossil-based and can be fully decomposed into CO_2 and water by microorganisms. Rather than being incinerated or gasified for energy, this waste stream would most likely be separated for composting and would not help to increase the biogenic fraction of RDF. Only biobased materials that are non-recyclable and non-biodegradable would influence the biogenic fraction that ultimately ends up as RDF. This is hard to predict as it depends on the development of recycling technology and industrial composting capabilities available. If the biogenic fraction of RDF were to increase over time though, as shown in both scenarios, this would lower the GWP of RDF treatments. However, although current forecasts envision growth of biobased materials, it currently has a lower priority than other efforts such as reducing plastics consumption and improving recycling which are higher in the waste hierarchy (IHS Markit, 2018).

7.3 Moving up the Hierarchy

The results from a business-as-usual future for 2050 support focusing efforts in levels higher than recovery in the waste hierarchy. In this year all of the waste treatment options under investigation lead to an increase in net GWP, implying that if this future were to unfold all of these options would exacerbate rather than mitigate climate change. This begs the question of what should then be done with this waste. Since it is clear that these end-of-life treatments such as gasification are no longer effective at reducing global warming, higher levels of the hierarchy should be prioritized. In theory, the most sustainable alternative for MSW is to not produce it in the first place. Ideally, this is where policy and decision makers should first focus. The utopian vision would be to create an economy that is entirely circular in which the term waste does not even exist, as every output of a process is an input for another. Despite this ideal vision, MSW will most likely continue to be generated in 2050, and research and policy should then focus on the levels of re-use and recycling. Recycling and re-use should be tackled by not only developing end-of-life solutions and technologies, but also explore improvements in the production or even design phase of products. Waste solutions should not be an afterthought once a product has been developed, rather they should be a proactive and integral part of the design process.

There are as well other waste treatment options that were not considered within this study that could still be viable from a GHG perspective in the 2050 BAU Scenario. For example, syngas-to-materials such as PHA plastics is a technology that is currently only proven at lab scale but could be a commercially viable option by 2050. These RDF plastics could potentially have a lower GWP than a reference plastic, whether bio or fossil-based, and could be the more sustainable way to treat waste. Such a plastic could also be cascaded both in time and use in the economy, and even further reduce the GWP associated with the material.

7.4 Cascading

In 2050, the BAU Scenario concluded that the gasification of RDF to methanol had a larger GWP than the reference biomethanol from wood chips. This suggest that methanol should be made from biomass and RDF should instead be gasified for energy. This conclusion should be critically assessed and interpreted with caution as it is limited and does not entirely take a systems view. Firstly, GWP is a very narrow focus in regard to the environmental impacts of cultivating biomass. In terms of GHG emissions it is true that methanol should be produced from wood chips rather than RDF, but there are broader consequences to consider. The majority of these wood chips are assumed to be virgin biomass from forestry and growing forests for methanol production could have detrimental effects on land use, water usage, biodiversity loss, or fertilizer use. These impact categories are not captured or quantified in this study and could even be worse environmentally than increases in GHG emissions. Secondly, the effects of cascading and temporal delays are not considered within this study. Both wood chips and RDF are treated as biomass equivalents in that 1 kg of carbon in wood has identical emissions to 1 kg of carbon in RDF. However, the wood chips from forestry are virgin biomass and are entering the carbon cycle for the first time when being converted to methanol. The carbon in the RDF however could be cascaded carbon, in that this may be the second or even third time it has entered the carbon cycle. If it were the carbon in particle board for example, it could have previously entered the system as virgin wood, been used and then downcycled to particle board, and then re-entered as unrecyclable waste for energy recovery. These two types of carbon are treated equally in this research when in reality cascaded biomass has shown to increase GHG emission reductions more than virgin biomass (Bais-Moleman et al., 2018). The temporal differences between the two types of biomass are also not captured in the LCA. Virgin wood being directly converted to methanol does not sequester carbon as long as the carbon in the RDF that may have been cascaded for several years. Using a cascading factor to differentiate the two types of biomass could perhaps offer a fairer assessment of waste treatment options by taking these factors into consideration (Bais-Moleman et al., 2018).

7.5 Adaptability

Despite ambitions to push waste up the ladder of the waste hierarchy, waste will continue to be generated for the coming decades and will still require sustainable solutions. The vexing problem is that regardless of the optimal treatment chosen, by investing in a technology for waste treatment, this gives waste a monetary value. When waste is commoditized, some party will profit from treating it which consequently incentivizes the generation of this waste. Constant waste generation is not only incentivized but even required to keep these technologies economically viable; for many waste technologies there needs to be economies of scale, and a constant supply of waste is needed to maintain operations and profits. This inherently incentivizes the generation of waste rather than diminishing it and can also trigger waste being traded internationally rather than treated domestically. The AEB plant in Amsterdam is a prime example of this; in 2018, they signed a 25-year contract with a waste company in the UK which will export over 1 million tons of RDF over the course of the contract (RISI, 2018). Such a contract clearly conflicts with the aim to reduce waste since both companies have invested in and guaranteed its continued generation. But this is true for the investment in any waste technology and there is a balance to be found between immediate solutions to meet current needs and the adaptability of these solutions if waste were to decrease.

Gasification is arguably the more adaptable technology studied and could respond best to reductions in the volume of MSW generated. This technology could provide an immediate solution while not hindering ambitions for waste reduction as it allows for flexibility of both feedstocks and end products. If waste generation was to rapidly decline, gasification plants could be fitted to use other types of biomass, such as forestry or agricultural residues, without large and capital-intensive modifications. This could also reduce the risk of financially incentivizing the generation of waste and hindering national goals of waste reduction. Incinerators could indeed also use other feedstocks such as wood pellets for bioenergy, however there is not the same flexibility to make an end product other than energy. Syngas on the other hand is such a versatile intermediate and can be catalyzed and upgraded into an entire portfolio of different products.

7.6 Biorefinery

Due to the flexible nature of syngas, one could envision a future RDF biorefinery in which waste is converted to a spectrum of products such as materials, chemicals, and energy. This study investigated if only energy or only methanol were produced, however a combination of these could be made. In the near term there will likely be enough MSW to meet European methanol demand plus a large excess that could be used for other products. In 2016, 128 million tons of non-recyclable MSW was incinerated or landfilled in the EU (Eurostat, n.d.). If the entirety of this was instead converted to methanol via gasification, this translates to 61 million tons of methanol. However, EU methanol demand is currently only around 7.6 million tons, thus there would be an excess of syngas to be used for other purposes (Pérez-Fortes et al., 2016). Of course, the EU could also export this methanol to meet the global demand that was approximately 80 million tons (International Energy Agency, 2016).

A syngas biorefinery could also provide more resilience for waste treatment, whether in response to fluctuating demands in the chemical or energy markets or decarbonization of reference products. If prices or demand were to change over time, the biorefinery could adjust its upgrading processes to align its supply with demand and maximal profits. Similarly, a biorefinery could adjust its output to maximize GHG reductions and help decarbonize a reference product that is hardest to decarbonize. For example, it could first begin producing methanol and if methanol were to decarbonize faster than say fertilizers because of biomethanol advances, the biorefinery could change catalysis steps to instead make fertilizer. A gasification biorefinery could also serve as a stepping stone to raise the TRL levels of products from syngas that are currently immature. The learning curves from gasification-to-methanol and gasification-to-energy could in turn help many other gasification-to-x technologies develop further.

Flexibility and resilience are key for waste treatment plants that will last for two or three decades. There thus needs to be the foresight to assess which technologies are viable from a GHG perspective long term as the reference products evolve and potentially decarbonize. The issue of waste is not an isolated one however, and depends not only on waste management decisions, but also on the development of the chemical, material, and energy sectors. There are thus tradeoffs and considerations that need to be explored by policy and decision makers to ensure that these different pieces of the puzzle fit together in a synergistic manner. If done properly, the treatment of waste could move beyond just disposing of a by-product of human activity and provide a solution for other sustainability issues of resource scarcity and global warming.

7.7 Limitations and Uncertainty

A large limitation of this study is that GWP is the only impact category assessed in the LCAs. This provides a very a narrow picture of the waste treatment landscape, as there are several other environmental impacts of waste such as ecotoxicity or water usage. Although these are also important to study, this research chose GWP as GHG emissions are a general measure used in EU policy and recognizes this as a limitation. Another limitation is that only a few, and not all potential alternatives for reference products are considered, although the most relevant alternatives are argued to be captured in this research.

The greatest uncertainty lies in the inputs for the gasification-to-methanol LCA due to intellectual property concerns and data restrictions from Enerkem. This process remains a black box, thus it was necessary to make assumptions where data was lacking. Therefore, it is assumed that the gasification process of Enerkem was identical to Valmet's, with only a small added burden from catalyst use for the conversion of syngas to methanol. It is very likely that the syngas conditioning and conversion requires additional energy and that the LCA slightly underestimates the total emissions. Despite this, the energy use may be small or negligible, as contacts at Enerkem confirmed that the only auxiliary energy used was electricity for utilities and small amount of natural gas for start-up and thermal oxidization. Contrarily, a possible overestimation of direct emissions for this process could have been made. After conducting a carbon balance, a carbon efficiency of 53% was calculated, assuming that all the carbon not embedded in the methanol itself was eventually emitted as CO_2 throughout the process, mostly likely during the RDF gasification step. The average carbon efficiency of conventional methanol from natural gas is 75%, and it is not definitively known why Enerkem's process is more than 20% lower (Swiss Centre for Life Cycle Inventories, 2007). A possible explanation is that the RDF composition assumed, specifically the 33.5% carbon, was a poor assumption. The more likely explanation though is that in general biomass is harder to gasify than fossil fuels, in that it results in the formation of heavy tars and gases. These tars and gases contain carbon that was not converted to syngas, and ultimately lower the carbon efficiency of the WtM process. Contacts at Enerkem later stated that this carbon efficiency can be as high as 70%, however the assumed carbon content of the waste was not explicitly mentioned, so it is unclear what could cause this range in efficiency. Another major uncertainty in the process is the assumption that the gas conditioning process is neither oxygen nor hydrogen deficient and no external gases are needed as an input. If the process were to require additional oxygen, this could greatly increase the GWP of the gasification-to-methanol as oxygen production is highly energy (electricity) intensive. This uncertainty would, however, diminish over time as electricity becomes more renewable.

Another important uncertainty to acknowledge is that the plants from which primary data was obtained did not process identical streams of waste and cannot be directly compared. The LCAs attempted to correct for these differences by adjusting and normalizing the LHV for incineration and gasification. However, the composition of the waste stream for the Enerkem plant is entirely unknown and is presumed to be the same as for the other technologies in order to allow for direct comparison. It is unknown to what degree the effect of waste composition would have on overall methanol production efficiencies.

The last shortcoming to address are the GWP values that are extracted from the Ecoinvent database. Many of these LCAs use outdated studies and some of this data was based on European data rather than the Netherlands specifically. The Ecoinvent values were deeper examined to deduce the boundaries and other assumptions made, and a conscious effort was made to ensure these were the same of the LCAs performed in this research. This was done to the greatest degree possible, but it is likely that some of the values used have slightly different boundaries or assumptions.

7.8 Further Research

The geographical scope of this research was limited to the Netherlands, but climate change is a global issue that is blind to national borders. A greater contribution could be made to the topic if further research similarly assessed waste treatment options in other EU or non-EU countries. The recommendations could highly vary for countries with different waste infrastructure and energy and chemical landscapes. Waste management decisions depend on these local circumstances and require customized solutions. Like climate change, MSW is also not restricted to national borders and is becoming an internationally traded commodity. It would thus be interesting to broaden the scope of this research globally and investigate GHG emissions considering this trade.

Another topic for further research is incorporating a cascading factor into the LCAs. As discussed previously, this study did not consider whether the carbon in the RDF or methanol was virgin or cascaded, and this could have an effect on the results if accounted for in some way in the methodology. This could prove difficult however as it would require a detailed tracking of materials within cycles of production, disposal, recycling, etc. Cascading could also relate to another branch of potential further research. This study only investigated energy and chemical production and could be expanded to also investigate the gasification-to-material technologies that will increase TRL levels in coming years. Cascading of material products versus chemicals and the resulting GHG implications could prove to be an interesting topic of future research and help to expand upon current LCA methodologies.

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