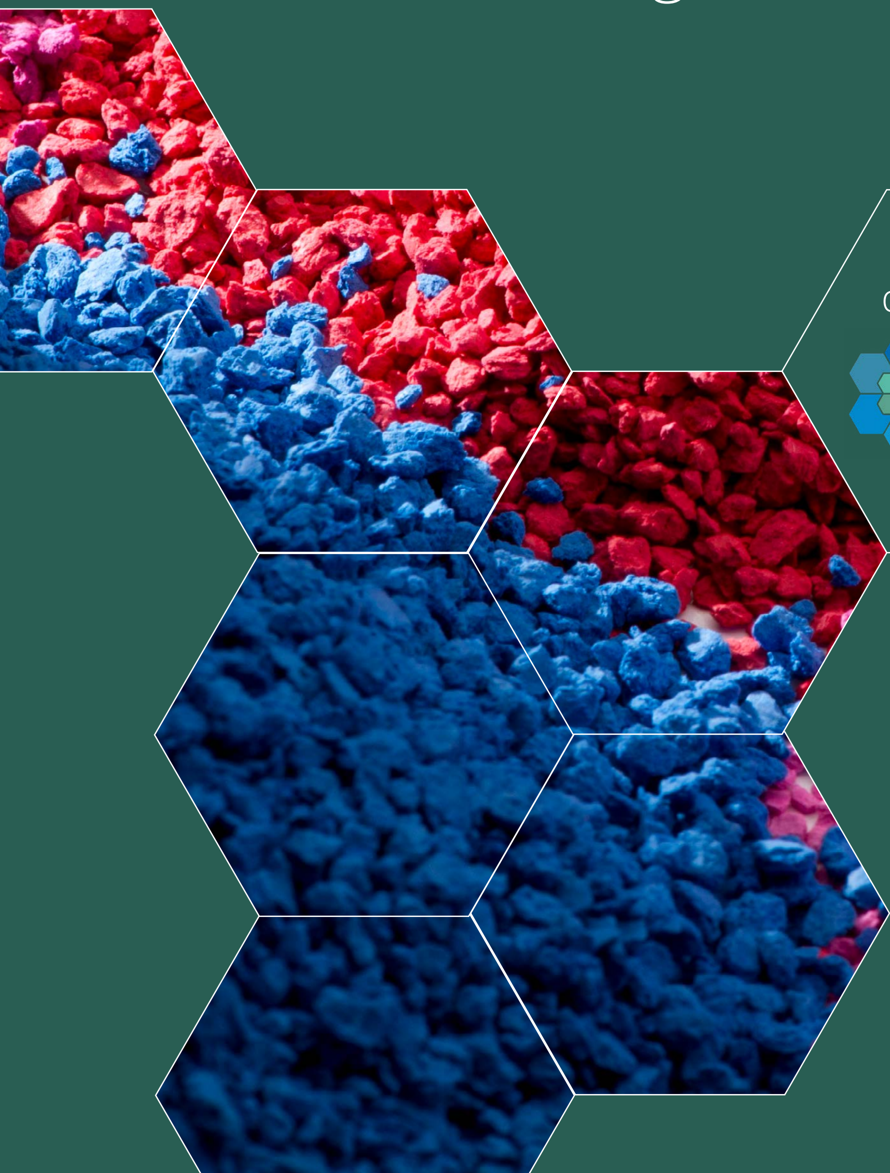
Chemical Recycling:

Greenhouse gas emission reduction potential of an emerging waste management route



Commissioned by

cefic

Study review conducted by Quantis

October, 2020

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Dear reader,
In a context where climate change, pollution and plastic waste can significantly harm our environment, it is crucial that immediate actions are taken.

Recent studies have predicted that, without a change in the course of action, the annual flow of plastic into the ocean could nearly triple by 2040, with a significant impact to the marine biodiversity. Improved and additional recycling solutions for plastic waste, such as chemical recycling technologies, can complement mechanical and dissolution recycling and reduce the leakage of plastics to the environment.

Chemical recycling technologies can also increase resource efficiency, closing the loop in the transition to a circular economy for plastics. These technologies can break down plastics and transform them into secondary raw materials to produce new chemicals and plastics of equivalent quality to those made from fossil resources.

In this report "Chemical Recycling: Greenhouse gas emission reduction potential of an emerging waste management route", Quantis has addressed the following questions based on existing material flow and life cycle assessment studies: What is the environmental impact of such technologies? Can chemical recycling technologies play a role in establishing a circular and sustainable economy?

Cefic supports the EU Green Deal and Europe's ambition to become climate neutral by 2050. The EU Circular Economy Action Plan is a cornerstone to meet this ambition. Chemical recycling technologies of end-of-life plastics can fill an enormous gap in the plastics economy to make it more circular. We invite policymakers to ensure that the right conditions exist across the EU to promote a competitive economic environment and enable large-scale investments to scale up and fully deploy chemical recycling.

Still, in order to ensure the full benefits of these technologies, it is vital they do not put the climate-neutrality goal at risk. This report, commissioned by Cefic, provides a first, valuable contribution to address that concern.

The conclusion of the report is indeed that chemical recycling technologies have the potential to avoid greenhouse gas emissions compared to today's conventional production processes and end-of-life treatments.

Marco Mensink,
Director General, Cefic

Disclaimer: Cefic commissioned Quantis to perform analyses of key studies and bring forward conclusions and recommendations from its independent viewpoint, in close collaboration with the sector.

PART 1

EXECUTIVE SUMMARY

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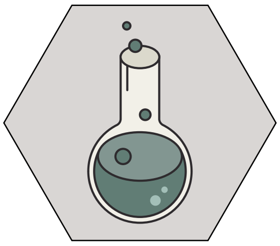

THE ISSUE AT HAND

Today, less than 30% of plastic is collected for recycling in Europe (2018 European Plastics Strategy). At the same time, the recycling rate for glass, paper, and metals in the EU is over 70% (ME 2019, Pauliuk et al. 2013). In December 2015, the Commission adopted an EU Action Plan for a circular economy. There, it identified plastics as a key priority and committed itself to prepare a strategy addressing the challenges posed by plastics throughout the value chain and taking into account their entire life-cycle'. In 2017, the Commission confirmed it would focus on plastics production and use and work towards the goal of ensuring that all plastic packaging is recyclable by 2030. The EC further describes a vision for Europe's new plastics economy: "Plastics and products containing plastics are designed to allow for greater durability, reuse and high-quality recycling. By 2030, all plastics packaging placed on the EU market is either reusable or can be recycled in a cost-effective manner." (EC Plastics Strategy 2018). Conclusively, then, the issue about plastic recycling is not simply about changing consumer behavior or improving collection. Rather, the solution requires systemic and technological changes in the way plastic is recycled. Experts agree that different plastics recycling technologies have to work in a synergistic and

Definition and overview of chemical recycling — also called feedstock recycling

Feedstock recycling, also known as chemical recycling, aims to convert plastic waste into chemicals. It is a process where the chemical structure of a polymer is changed and converted into chemical building blocks, including monomers, that are then used again as a secondary raw material in chemical processes. Feedstock recycling includes processes such as gasification, pyrolysis, solvolysis, and depolymerisation, which break down plastic waste into chemical building blocks, including monomers, for the production of plastics. (Cefic 2020), (ISO 15270 2008)

Some chemical recycling technologies are still under development and are not yet viable, deployable options for widespread recycling of plastic waste. Each technology has a different environmental footprint and subsequent contribution toward the circularity of plastics. Whereas examples like pyrolysis (e.g., BASF's ChemCyclingTM) and gasification (e.g., Enerkem in Canada) are currently used at commercial scale, other chemical recycling technologies are only available in pilot phases. Some chemical recycling technologies will most likely enter the plastics value chain at the higher end, such as depolymerisation toward certain monomers (e.g. polystyrene, polyamides, or polymethyl methacrylate). Improved and additional recycling solutions for plastic waste, such as chemical recycling technologies, can complement mechanical recycling and dissolution recycling, and reduce the leakage of plastics to the environment.

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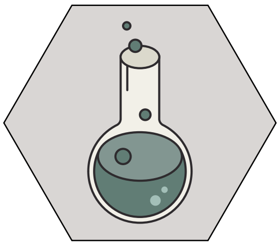

complementary way to achieve higher plastic recycling rates and develop a stronger circular economy for plastics. Still, in order to ensure the full benefits of a low-greenhouse gas (GHG) emissions circular economy, it's important that complementary technologies enable the recycling and usage of recycled material as feedstock material with a low overall carbon footprint.

CHEMICAL RECYCLING: A VIABLE SOLUTION?

Chemical recycling technologies can respond to our global **resource challenge** by increasing the proportion of end-of-life plastics that are recycled and provide feedstock, to replace feedstock from traditional fossil sources. In addition, chemical recycling can contribute to the **circular economy** by closing material and, potentially, value chain loops. Chemical recycling is a more sustainable end-of-life management option for mixed plastic waste compared to incineration, landfilling, or — the worst-case scenario — environmental leakage to soil and water bodies.

POTENTIAL ENVIRONMENTAL BENEFITS OF CHEMICAL RECYCLING

Development and deployment of new circular technologies can offer **environmental benefits compared to existing ones**, such as reduced GHG emissions, reduced primary resource usage, or reduced waste. Using recycled feedstock material enables a concomitant reduction of primary source- based production and associated resource depletion. Still, to assess chemical recycling's true environmental impact, its **environmental footprint, including GHG emissions avoided**, should always be considered from the **full life cycle perspective**. For example, if a plastic waste stream is chemically recycled rather than incinerated, emissions avoided by eliminating the need for incineration should be taken into account when calculating the end-of-life solution's environmental footprint. Figure 1 displays the fossil-based plastics value chain and potential end-of-life treatment options.

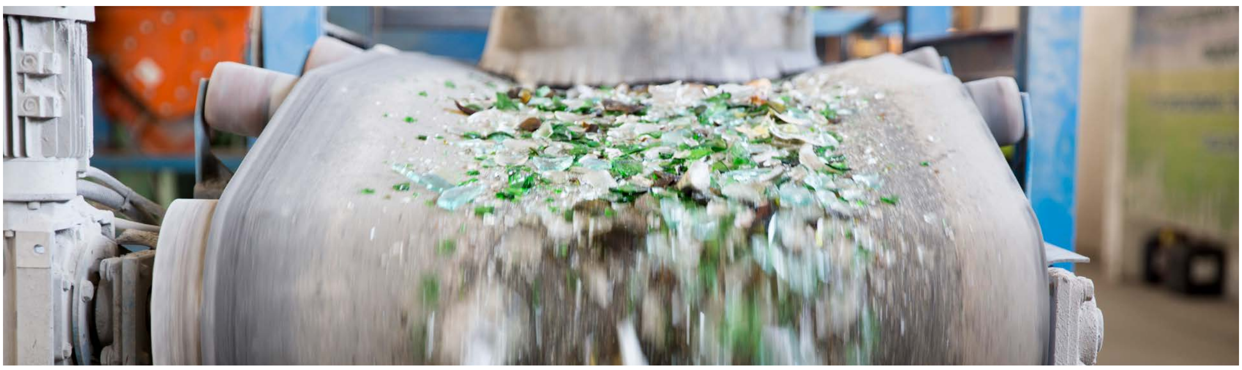

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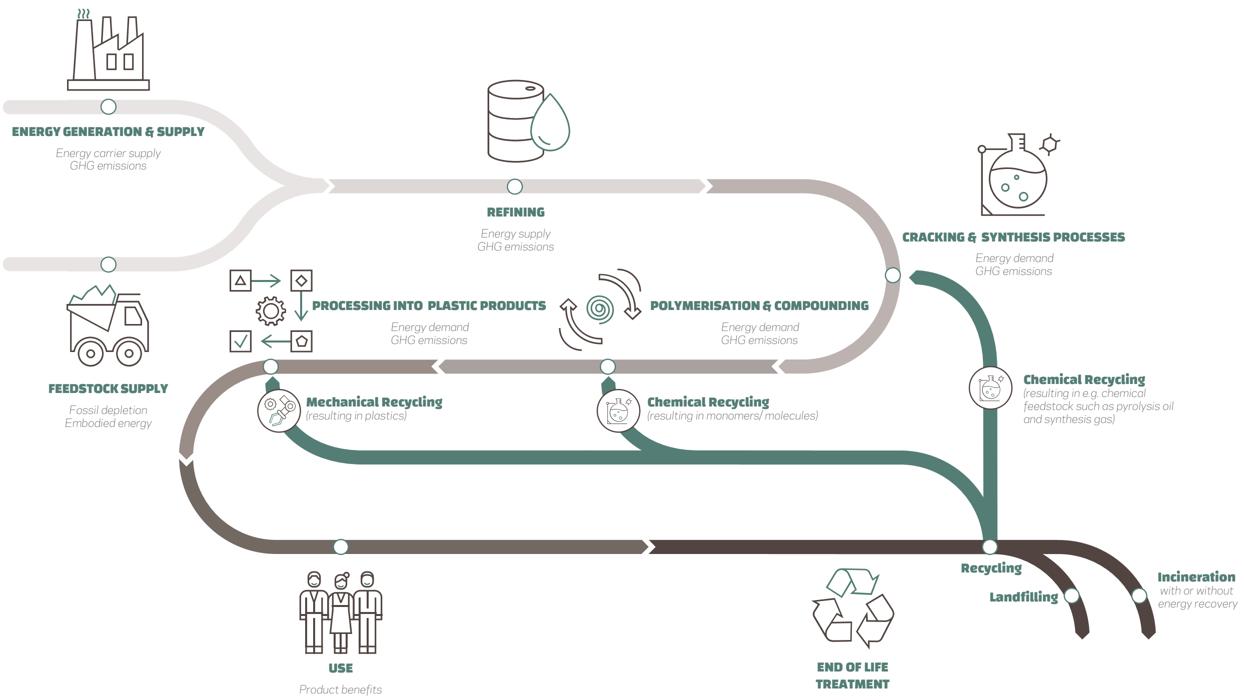
Figure 1 — *Value chain of fossil-based plastics, including mechanical and chemical recycling options*



CHALLENGES AND OUTLOOK

While chemical recycling has great potential to improve plastic recycling rates, avoid GHG emissions, reduce fossil-based feedstock demand, and promote a circular economy, feedstock recycling technologies are still in the early stages of industry scale use. For the chemical industry, life cycle assessment is the key method used to assess the enviromental benefits and weaknesses of chemical recycling in a consistent and comparable way. In order to get a clear understanding of chemical recyling's environmental performance, future LCA studies should provide a stronger focus on the material efficiency of recycling technologies, surrounding infrastructure, transport logistics, and an appropriate evaluation of the maturity of considered technologies.

PART 2

STUDY OVERVIEW

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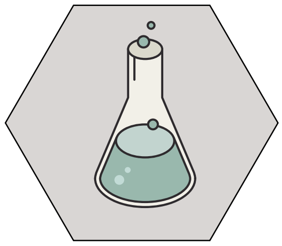

A REVIEW OF FOUR PUBLISHED STUDIES ON CHEMICAL RECYCLING

This analysis summarizes findings on chemical recycling taken from four recent studies, chosen to provide a comprehensive and realistic picture of the environmental benefits of using chemical recycling:

- **Material Economics** (2019). Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry. [Material Economics (2019)] and Material Economics (2018). The Circular Economy a Powerful Force for Climate Mitigation Transformative innovation for prosperous and low-carbon industry. [Material Economics (2018)]

- **Agora Energiewende und Wuppertal Institut** (2019): Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement. Berlin, November 2019. [Agora (2019)]

- **CE Delft: Exploratory study on chemical recycling.** Update 2019 [CE Delft (2019)]

- **BASF SE** (2020): ChemCycling™: Environmental Evaluation by Life Cycle Assessment (LCA). [BASF (2020)].

A special focus has been given to assess GHG emissions savings and avoidances — or, in other words, the "carbon balance" of chemical recycling compared to alternative solutions from a value chain perspective.

The first two studies mentioned provide an overview of how a carbon-neutral industry can be shaped and incentivized from 2030 and beyond in Europe and Germany. The latter two are Life Cycle Assessment (LCA) approaches that compare existing plastic waste treatments and primarily fossil-based feedstock usage with chemical recycling technologies (pyrolysis) and the use of recycled feedstock.

The four studies work with different approaches, displayed in figures 2 and 3 below.

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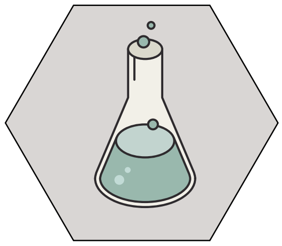

Figure 2 — *Exemplary material flow analysis scheme as used in ME (2018, 2019) and Agora (2019)*

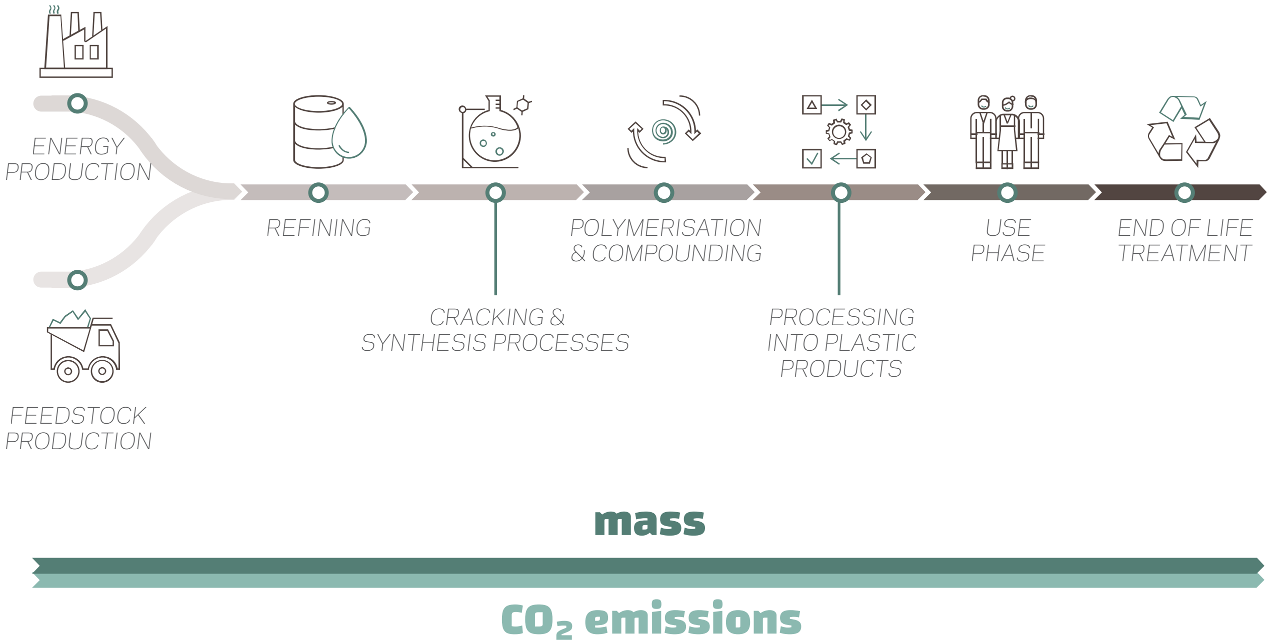

Figure 2 describes the material flow analysis approach, which summarizes feedstock flows, product mass flows, and carbon dioxide emissions that occur along each process step in a fossil-based plastics value chain. The material flow analysis deployed by the Material Economics and Agora Institute studies shows the most important carbon dioxide emissions along the plastics value chain, and is used to predict changes stemming from future technological developments.

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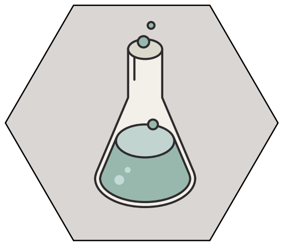
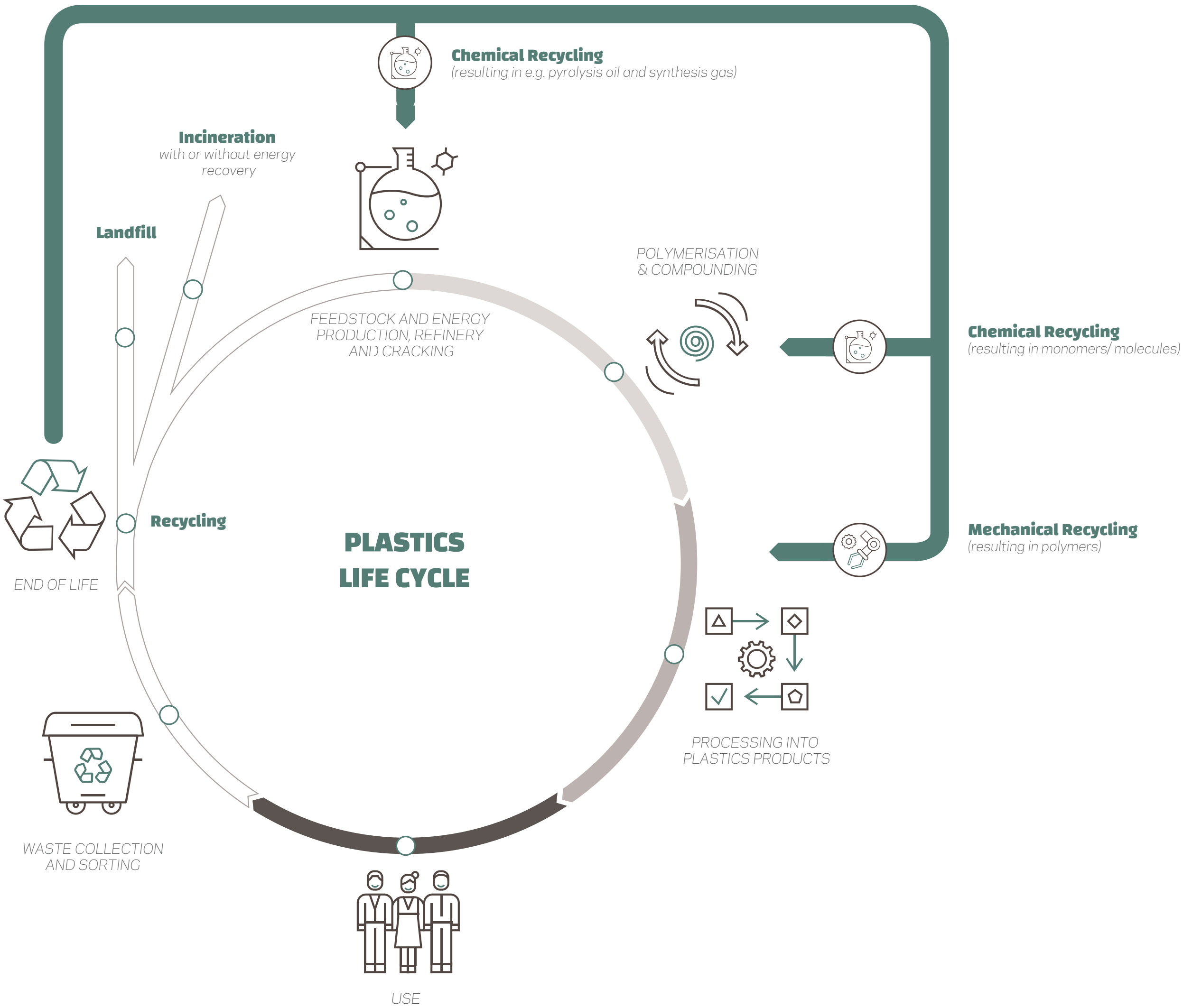


Figure 3 — *Exemplary life cycle assessment scheme*



In comparison, Figure 3 depicts the LCA approach and shows the holistic life cycle of a plastic product (e.g., 1 kg of plastic packaging), comparing different recycling and primary feedstock alternatives based on fixed system boundaries. An LCA covers various environmental impact categories, including **climate change**, which summarizes all anthropogenic GHG emissions (e.g., CO_2, methane, nitrous oxides, etc.) throughout a product's life cycle. In addition, an LCA can cover **avoided emissions** if, for example, a by-product such as heat or secondary plastics enables the avoidance of the primary production of energy or plastics. These avoided emissions can be attributed to the original product life cycle, thus

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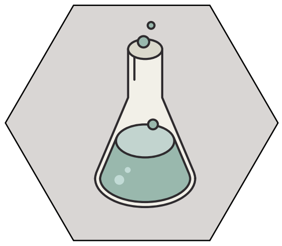

improving the product's overall environmental performance.

The CE Delft and BASF studies focus on technological comparisons, aiming to analyze the environmental impact of using chemical recycling technologies compared to conventional plastic waste treatment. Both studies clearly show GHG emission savings and benefits from feedstock recycling compared to plastics production from virgin fossil feedstock. Avoided GHG emissions can be attributed to the avoidance of crude oil extraction and refinement (to naphtha) and avoiding the incineration of end-of-life products.

In comparison, both the Material Economics (ME) and Agora studies take a systemic material flow analysis approach[1] and attempt to prove how feedstock recycling can contribute to low industrial GHG emissions from 2030–2050. Both author groups take technological sector developments into account, but do not necessarily focus on a single or specific chemical recycling technology.

The ME and Agora studies base information about chemical recycling technologies on scientific literature and technology projections rather than on industrial processing data. As these studies work with future projections for technologies with low technology readiness levels (TRL), they can be used to provide an outlook for the plastics industry, but not as true descriptors or performance measurements of currently available or even soon-to-be-available chemical recycling technologies.

The CE Delft study uses information from demonstration plants that are in use, but not necessarily at commercial scale yet. Only the BASF study relies on production information at an industrial scale for one chemical recycling technology (pyrolysis). Information about material efficiency and technology yields are considered in the BASF study, but are not published or available for the other studies. Table 1 and 2 provide an overview of the studies used and summarizes their high-level conclusions.

Table 1 — *Studies overview*

	MATERIAL FLOW ANALYSIS APPROACH		COMPARATIVE LCA APPROACH	
Sources	ME 2018 and 2019	Agora	CE Delft	BASF
Working hypothesis and summary	- Operationality of circular economy in Europe - ME 2019: stronger focus on circularity	- Decarbonization roadmap for Germany - How to incentivize investment in innovative technologies through policy measures	- Summary of chemical recycling technologies in the Netherlands - Links data on suitable waste flows with indicative key figures for climate emissions	- Comparison between plastics production from pyrolysis oil and naphtha, additional comparison with other end-of-life treatments like incineration and mechanical recycling
Model approach	- Plastics material flow analysis combined with a carbon dioxide emissions model	- Plastics material flow analysis combined with a carbon dioxide emissions model - Adapted for Germany	- Screening LCA model - Comparison between the recent status quo reference case vs. innovative chemical recycling approach	- ISO 14040/44 LCA study - Critical review by three independent experts - Three separate studies (waste, product, and plastic quality perspectives)[2]
Analyzed system	- Chemical recycling used in the plastics industry as complementary end-of-life treatment to existing technologies	- Chemical recycling used in the chemicals industry as complementary end-of-life treatment to existing technologies	- Reference cases vs. chemical recycling technologies - Reference cases: recycling losses to incineration, mixed plastics to downcycling, PET wastes to be stored or incinerated	- Waste perspective: pyrolysis or incineration of mixed plastic waste - Product perspective: plastics based on pyrolysis oil or from primary fossil resources - Plastics quality perspective: virgin plastics with three end-of-life options
Value chain steps	- Feedstock and electricity production, refining, cracking and other foreground processes, polymerisation and blending, end-of-life treatment	- Feedstock and electricity production, refining, cracking and other foreground processes, polymerisation and blending, end-of-life treatment	- Plastic waste treatment and substituted products	- Feedstock, chemical processes (e.g., steam cracking, polymerization), end-of-life treatment - Substituted products
Data basis	- Eurostat - PlasticsEurope Eco-profiles - Zhu et al. 2018 - IEA technology mix, decarbonization by 2050 scenario ME 2019: - DECHEMA 2017 - Thunman et al. 2019	- ME 2018 & ME 2019 - UBA - Calculations made by Wuppertal Institute - VCI - Destatis - Industry information from: SABIC, BASF, Waste to Chemicals	- CE Delft studies: Ioniqa screening LCA, Rotterdam report (AkzoNobel) - PlasticsEurope - EUROSTAT - Ecoinvent background model	- Data from existing commercial plants - BASF internal databases -Other databases (e.g., Sphera/GaBi, Ecoinvent)
Time horizon	- 2030–2050 projection	- 2030–2050 projection	- Status quo in 2020	- Status quo in 2020 combined with projections toward 2030 - Future development of pyrolysis and the waste sector in Germany in 2030

2 Two of the studies are based on mass balance approach. Mass balance accounting is one of several well-known chain of custody approaches, designed to trace the flow of materials through a complex value chain (Ellen MacArthur Foundation: Enabling a circular economy for chemicals with the mass balance approach, 2019; *https://www.basf.com/global/en/who-we-are/sustainability/whats-new/sustainability-news/2019/EllenMacArthurfoundation-White-Paper-Mass-balance.html*).

PART 3

KEY FINDINGS

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Chemical recycling technologies offer the potential to avoid GHG emissions that can occur in both the production of feedstock and from the current end-of-life treatment of plastic.

The four studies and both approaches used — material flow analysis and comparative LCA — demonstrate the CO_2 reduction potential of chemical recycling. The authors of this summary emphasize that the four studies considered show major differences in:

- Scope (i.e., processing steps covered in the plastics value chain)
- Time horizon
- Model approach (i.e., materials flow analysis versus LCA approach)
- Results reported as carbon dioxide emissions reductions (material flow analysis) versus GHG emissions reductions (LCA)
- Maturity of technologies and data used
- Geographical scope

Table 2 — *Key CO_2 emissions results – A detailed analysis of the results can be found in the annex.*

	MATERIAL FLOW ANALYSIS APPROACH		COMPARATIVE LCA APPROACH	
Study	ME 2018 and 2019	Agora	CE Delft	BASF
Key GHG emissions savings statement	Product perspective (cradle-to-grave): Chemical recycling can achieve around 0.2 t CO_2 per t plastics produced — compared to 2.3 t CO_2 from conventional production using fossil feedstock.	Product perspective (cradle-to-grave): Chemical recycling can achieve around 0.3 t CO_2 per t plastics produced — compared to the 2.3 t CO_2 from conventional production using fossil feedstock.	-	Product perspective comparison of plastics based on pyrolysis oil and conventional plastics from primary fossil resources (naphtha): Conventional production of 1 t LD — PE emits, in total, 1.9 t CO_2eq. For the production of 1 t LDPE via pyrolysis, 2.4 t CO_2eq less CO_2 emissions can be accounted.
			Waste perspective — comparison of pyrolysis and incineration of mixed plastic waste: Mixed plastic waste is currently incinerated. This produces a total climate impact of approximately 1.5 t CO_2 eq./t input material. Chemical recycling (pyrolysis) of the same input material results in 1.5 to 2 t less CO_2 eq./t.	Waste perspective — comparison of pyrolysis and incineration of mixed plastic waste: Pyrolysis of mixed plastic waste emits 50 % less CO_2 than incineration of mixed plastic waste. Specifically, the study found that pyrolysis emits 1 t less CO_2 than incineration per 1 t of mixed plastic waste.

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Due to the study differences explained above and displayed in Table 1, direct comparisons in terms of GHG emissions avoided are not possible, and could be overly simplified.

Chemical recycling technologies are expected to play an essential role in establishing a circular and sustainable economy in the chemical industry.

Mechanical recycling is a common way to recycle plastics today. However, not all plastics can be recycled using this technology, and plastic waste that reaches recycling facilities is often contaminated or mixed. This hinders recycling rates and results in large quantities of plastics being incinerated, sent to landfills or, in worse-case scenarios, leaking into the environment.

Chemical recycling could play an essential role in a circular plastics economy as a complement to mechanical recycling. According to ME (2019), the two approaches combined could bring recirculation of plastics to as much as 62% of total production by 2050. Plastics would then be nearly as circular as the major metals (recycling rates for steel and aluminium are 85% and around 70%, respectively).

ME (2018), ME (2019), and Agora (2019) attempt to evaluate the degree of impact this synthesized approach would have by 2050. As some novel technologies are not yet in use on a commercial scale, results presented should be considered only as a forecast that needs to be confirmed as soon as the technologies described mature.

CE Delft (2019) deploy an LCA screening approach to compare the reference case (status quo) with an already-existing alternative (at demonstration scale) for chemical recycling, and credits the avoidance of naphtha production to producing pyrolysis oil, compared to the reference case. The three LCAs conducted by BASF mirror the CE Delft results with regards to circularity. ChemCyclingTM technology, one of the first viable chemical recycling technologies, proves that pyrolysis can close the plastics loop by producing LDPE via pyrolysis, including excess energy substitution.[3]

3 The ChemCycling pyrolysis generated excess heat, which can be used elsewhere.

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Further learnings from the studies reviewed

Some additional key learnings identified from the ME (2018, 2019), Agora (2019), CE Delft (2019), and BASF (2020) studies include:

- It is hard to predict chemical recycling's full environmental impact and GHG emissions reductions potential due to varying technology readiness levels (TRL). As a result, the picture on suitable intake materials, yields, and substitution potential may be incomplete.

- The ME and Agora studies describe future technology pathways, whereas CE Delft compares existing technologies at a demonstrative level, and BASF at a commercial scale.

- The German-focused Agora (2019) and ME (2018, 2019) studies are based on existing literature. The assumed chemical recycling technologies and other innovative chemical network technologies (e.g., electrical steam cracker) are still in the planning feasibility stage (low TRL) and are not mature enough to provide suitable information about process emissions, yields, and substitution potential.

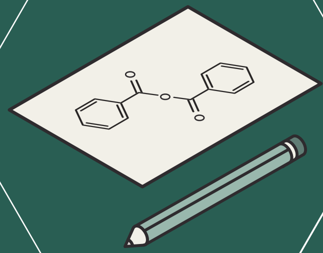
- The four studies analyzed use averaged data as references for the olefin/polyolefins based on Plastics Europe data, which assumes the use of a classic steam cracker powered by fossil fuels. However, the plan for chemical recycling of polyolefins is to feed the naphtha-like stream in a steam cracker together with the petroleum-derived naphtha. Both feedstock streams are meant to use the same state-of-the-art cracker technology — meaning this data reference should change in the future.

- The Netherlands-focused CE Delft (2019) study uses some primary data from the industry, but data quality varies. Additionally, information from the industry at demonstration scale needs to be proven to be viable at a commercial scale, especially in terms of emissions, yields, and credits for avoided production. The study's sources also include some currently immature technologies. For example, the IONIQA process for PET recycling is at demonstration scale. The technology is at TRL-5, meaning energy data and yield might be too optimistic and need to be improved for use in further studies.

- Plastic waste data (e.g., collection rates, sorting, definition of waste streams) and prices are mostly considered as a black box data in all four studies.

PART 4

CONCLUDING REMARKS



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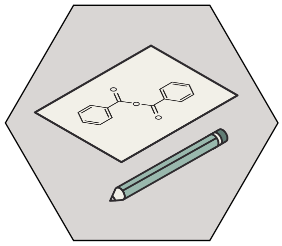

Challenges and future steps forward to implement chemical recycling in the European industry

While chemical recycling has great potential to improve plastic recycling rates, reduce our reliance on fossil-based feedstock, and promote a circular economy, feedstock technologies are still in the early stages. Major investments are needed to accelerate the development of technologies to mark and trace the origin of the different plastic waste types, automate sorting and processing, and chemically recycle plastics. Chemical recycling is also not necessarily a plug-in technology, and changes in logistics, infrastructure, and collection systems are necessary. This is important for feasibility and costs, as plug-in solutions are seen as most sucessful in the short term.

Both approaches analyzed — material flow analysis and LCA — show that chemical recycling complements and provides an alternative to mechanical recycling. It could play an essential role in a future low-GHG emissions economy, as shown by GHG emission savings throughout the plastics value chain.

The core strength of the ME and Agora studies is their outlook toward a low carbon, circular economy for plastics by 2050. They also describe in detail the required incentives and investments in future emerging technologies, and the uncertainty in predicted results.

The CE Delft and BASF studies present LCA-based approaches with likely lower uncertainty as they both rely on chemical recycling technology information that is already available at a more mature TRL. In addition, the LCA approach focusses more on the value chain and depicts the circularity of products in greater detail.

In summary, both approaches show the environmental benefits of chemical recycling technologies:

- Chemical recycling can **avoid the incineration of plastics and corresponding end-of-life GHG emissions**, with a favorable overall GHG emissions balance.

- **Plastic waste can be used as feedstock material**, thus avoiding the exploration and refinement of crude oil and corresponding GHG emissions, with a favorable overall GHG emissions balance.

- Process energy (in the case of pyrolysis and gasification) to heat up systems are self-sustaining and can replace the need for external energy, since energy comes from the process itself. This makes **plastics feedstock production independent from other fossil resources and avoids GHG emissions from energy production coming from fossil resources as purchased natural gas is avoided.**

- **Plastic can become a fully circular material at a large scale through a smart combination of mechanical and chemical recycling.** This finding is especially emphasized in the two

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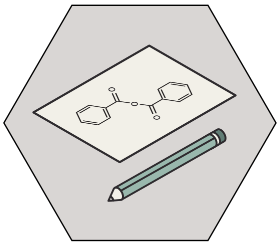

Material Economics studies and the Agora study, which describe chemical recycling as a complementary technology to mechanical recycling.

Assessing the overall carbon footprint savings or "avoided emissions" of new technologies requires a full life cycle perspective. The chemical industry uses the standardized LCA approach to measure and describe the carbon footprint/GHG emissions from chemical recycling technologies contributing to plastics circularity.

LCA is the key method used to assess the enviromental benefits of chemical recycling in a consistent and comparable way. The method provides clear guidance to:

- Avoid potential double counting
- Set clear system boundaries to depict the plastics value chain and establish a systemic approach to compare systems and respective functions used (e.g., comparison of end-of-life options for plastics or plastics produced from different feedstocks)

Future studies should provide a stronger focus on:

- **Material efficiency** for both complementary recycling methods — mechanical and chemical
- **Time horizon** for the considered technology
- **Surrounding infrastructure** such as electricity grid mixes, waste collection, and sorting
- **Transport logistics**
- **TRL of the technologies** used

The LCA-based studies presented provide preliminary insights on GHG emissions savings using chemical recycling technologies compared to less sustainable end-of-life management such as incineration. Future LCA-based studies can help provide further data for making such claims. Industry participation remains important in order to support future studies with real process information, as both the CE Delft and BASF studies demonstrate.

REFERENCES

Agora (2019)	Agora Energiewende (2019). Klimaneutrale Industrie Schlüssel-technologien und Politikoptionen für Stahl, Chemie und Zement
BASF (2020)	BASF SE (2020): ChemCyclingTM: Environmental Evaluation by Life Cycle Assessment (LCA)
CE Delft (2019)	Exploratory study on chemical recycling. Update 2019
Cefic (2020)	Cefic Position Paper 2020. Introducing chemical recycling: Plastic waste becoming a resource
DECHEMA (2017)	DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.
Deloitte (2015)	Deloitte and Plastics Recyclers Europe (2015). Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment. http://www.plasticsrecyclers.eu/sites/default/files/BIO_Deloitte_PRE_Plastics%20Recycling%20Impact_Assesment_Final%20Report.pdf
EC Plastics Strategy 2018	European Commission: Plastics Waste Strategy (2018), https://ec.europa.eu/commission/news/eu-plastics-strategy-2018-nov-20_en
IPCC (2006)	IPCC Intergovernmental panel on climate change, Riitta Pipatti, Chhemendra Sharma, Masato Yamada, Virginia Carla Sena Cianci, et al. (2006). Chapter 2 Waste generation, composition and management data. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006(Volume 5: Waste). https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_2_Ch2_Waste_Data.pdf.
ISO 15270 (2008)	ISO 15270:2008. Plastics — Guidelines for the recovery and recycling of plastics waste
ME (2018)	Material Economics (2018b). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.
ME (2019)	Material Economics (2019). Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry.
Pauliuk et al. (2013)	Stefan Pauliuk, Tao Wang and Daniel B. Müller (2013). Steel all over the world: Estimating in-use stocks of iron for 200 countries. Resources, Conservation and Recycling, 71. 22–30. DOI:10.1016/j.resconrec.2012.11.008.
Plastics Europe (2018)	Plastics – the Facts 2018. www.plasticseurope.org.
Plastics Europe (2019)	Eco-profiles. https://www.plasticseurope.org/en/resources/eco-profiles.
Zhu et al. (2018)	Zhu, J.-B., Watson, E. M., Tang, J. and Chen, E. Y.-X. (2018). A synthetic polymer system with repeatable chemical recyclability. Science, 360(6387). 398–403. DOI:10.1126/science.aar5498.

Annex

IN-DEPTH ANALYSIS OF GHG EMISSIONS AVOIDED AND UNDERLYING MODEL ASSUMPTIONS

The studies considered here follow different ways of estimating GHG emissions from chemical recycling and its potential savings. Materials Economics 2018, 2019, and Agora attempt to project a low GHG emissions economy by using a material flow analysis. The material flow analysis applies alternative technologies, predicted for use in Europe (ME 2018, ME 2019) or Germany (Agora 2019) in the future (2030–2050). In comparison, CE Delft (2019) deploys a life cycle assessment (LCA) screening approach to analyze the technological status quo of chosen chemical recycling technologies in demonstration scale against a reference system, described as state-of-the-art plastics disposal (incineration or mechanical recycling) in the Netherlands. BASF (2020) presents a critically reviewed ISO 14040/44 LCA study that provides an overview of the environmental benefits, including GHG emission savings, for their industrial scale pyrolysis technology.

ME (2019) states that chemical recycling could achieve very low atmospheric emissions of around 0.2 t CO_2eq per ton of plastics compared to the 2.3 t CO_2eq from the state-of-the-art production of fossil feedstock necessary to produce raw material feedstock.

This 2.3 t CO_2eq figure is associated with the material acquisition and pre-processing life cycle stages: feedstock and electricity production, refining, cracking and other foreground processes, polymerisation and blending. It has been calculated as a weighted average of the emissions factors of the most common plastics types (PE, PP, PVC, PET, PS, PUR) based on the ecoprofiles published by Plastics Europe (2019), the market share of different polymers (Plastics Europe 2018), and a Deloitte study (2015). ME (2018)'s reported 2.5 t CO_2eq values is based on the same assumptions using ecoprofiles data available up to 2018.

Concurrently, to arrive at 0.2 t CO_2eq per ton of plastics, ME (2019) builds off DECHEMA (2017) and explores two chemical recycling processes — gasification and pyrolysis — that convert plastics into simpler molecules. Low-CO_2 hydrogen from either electrolysis or steam methane reforming with carbon capture and storage (CCS) is a major input in gasification. For pyrolysis, the central contributor to reduced GHG emissions is the electrification of the cracker stage. For low emissions, the overall carbon mass balance must be very high so that the amount of CO_2 released is minimal. In a net-zero system, nearly all carbon inputs must be transformed into product outputs. For gasification, this requires adding more hydrogen. For pyrolysis, another process step must be added so the fuel-grade by-products from cracking (largely methane) are not burnt and release CO_2, but are further processed into high value chemicals (HVCs) instead. If this is done, the percentage of carbon that escapes as CO_2 can be below 5% of the total.

In the pyrolysis route, plastics waste is processed into naphtha-like pyrolysis-oil, which is used to produce HVCs through steam cracking. The fuel gas consists predominantly of methane, which can be further processed into methanol and olefins through methanol to olefins (MTO) to increase the

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yield. These steps result in a total yield of 0.9 kg plastics per kg plastic waste, and CO_2 emissions of 0.3 kg CO_2 per kg of plastics produced. In the gasification route, plastic waste is gasified into sweet syngas with the addition of hydrogen, followed by methanol synthesis and subsequently, production of plastics through MTO. This route results in a total yield of 0.9 kg plastics per kg of plastic waste, and CO_2 emissions of 0.15 kg CO_2 per kg plastic waste, assuming zero to low CO_2 production of hydrogen.

Provided that chemical production systems have been adapted to accommodate the required technological adjustments, emissions associated with chemical recycling could be as low as 0.2 t CO_2eq per ton of plastics.
It is also important to note the end-of-life emissions savings that chemical recycling may offer. Incineration is a common end-of-life treatment, and results in a further 2.7 t CO_2eq/t of plastic waste. These are CO_2 emissions from embedded carbon released during incineration, without taking into account avoided emissions from energy credits during incineration.
ME (2018) describes CO_2 emissions of 1 kg CO_2/kg processed plastic waste based on a scientific article by Zhu et al. (2018).

CE Delft (2019) notes that the climate change impact differs by recycling technique. Additionly, due to the diverse technologies and environmental performance used, it is not advisable to view chemical recycling as a singular process technique. For example, the impact of techniques such as pyrolysis and gasification are estimated between 0 to -0.5 t CO_2eq/t input, while the impact of techniques that break down polymers into monomers for direct use (such as depolymerisation and solvolysis), is estimated up to -1,5t CO_2eq/t input. More details are provided below:

- Recycling rejects are currently incinerated in AECs. This produces a total climate impact of approximately 1.5 t CO_2eq/t input material (including credit from avoided energy production). Chemical recycling, by contrast, results in a climate impact between 0 and -0.5 t CO_2eq/t input material. Compared to AECs, emissions associated with the process are lower (only use of energy, no combustion of plastics), while in particular syngas and diesel-type are produced. This production avoids other production chains (natural gas, conventional diesel). The total reduction in climate impact, then, amounts to 1.5 to 2.0 t CO_2eq/t recycling failure. It should be noted, however, that the study's authors mainly use data from demonstration plants and deemed process emissions in particular as too optimistic compared to what might be emitted from processes deployed at a commercial scale.

4 The value has been calculated based on IPCC (2006), using the following formula:
kg CO_2 = kg waste for incineration * oxidation factor of carbon in incinerator (0.98) * conversion factor of C to CO_2 (3.67) * Σ(waste fraction (%) * dry matter content (%) * carbon content (g/g dry weight)).
The dry matter content of plastic waste is equal to 1. The carbon content of plastic waste is 0.75 (g C/g dry weight waste). Moreover, the end-of-life emissions vary between different plastics types. The emissions are higher for incineration of e.g. PS and PE (around 3 kg CO_2/kg plastics) and lower for e.g. PP and PUR (around 2.5 kg CO_2eq/kg plastics). In summary, ME (2019) and ME (2018) have used 2.7 kg CO_2eq/kg plastics for all incinerated end-of-life plastics

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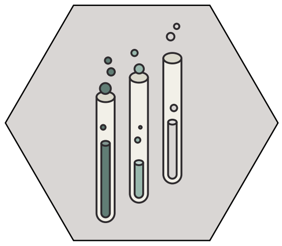


- For the mixed plastic stream (DKR 350) that is produced from source-separated material, the climate impact of chemical recycling techniques is estimated to be the same as the impact of recycling failure. However, the reference is different. The mechanical recycling of DKR 350 into plastic recyclate for thick-walled applications ("processing DKR 350") produces a climate impact of approximately -0.5 t CO_2eq/t input material. This is partly because the use of the recyclate prevents the production of steel and virgin plastic. Reduction of the climate impact of chemical recycling, therefore, is between -0.5 t CO_2eq/t DKR 350 (climate impact increases) and 0 t CO_2eq/t DKR 350 (climate impact remains the same).

- For PET waste, mechanical recycling results in a climate impact of -2.3 t CO_2eq/t, while chemical recycling (magnetic depolymerization) results in -1.5 t CO_2eq/t. In both cases, the result is negative because the production of virgin PET is prevented. However, in this comparison it should be noted that mechanical recycling is not a perfect reference technique for the PET trays.
- Main assumptions and considerations:

o It has been assumed that mechanical recycling, magnetic depolymerization, and solvolysis takes place in the Netherlands. However, these processes also replace the production of virgin PET and EPS. It has been assumed that two-thirds of this virgin production takes place in the Netherlands and one-third abroad, based on statistical data on the import and Dutch production of plastics.

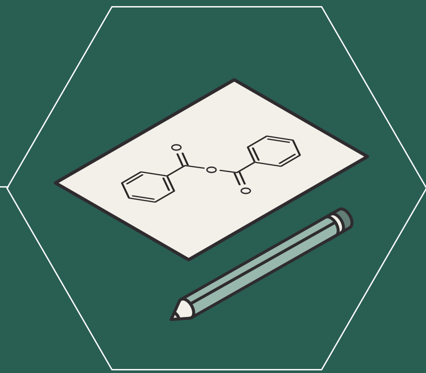
o Currently, the DKR 350 fraction is mainly processed in Germany.

o It has been assumed that the selected techniques can be used on a large scale and that the selected plastic waste streams are appropriate.

o It has been assumed that products made during processing are marketed (thus avoiding other production chains). For example, it has been assumed that all syngas that would be produced by integrated hydropyrolysis could be used in the Netherlands, preventing conventional production.

o The climate impact of transport when importing plastic waste is not included.

The waste perspective study from BASF (2020) states that pyrolysis of mixed plastic waste emits 50% less CO_2 than the incineration of mixed plastic waste. From a product perspective (comparison of plastic production from pyrolysis oil and naphtha), CO_2 emissions are saved when plastics are based on pyrolysis oil instead of crude oil based naphtha. The study shows this for the production of LDPE. 1 t LDPE produced from pyrolysis oil emits 2.3 t less CO_2 than 1 t LDPE produced from fossil naphtha. From a third perspective (plastic quality), BASF concludes that the manufacturing of plastics using either chemical recycling (pyrolysis) or complementary mechanical recycling of mixed plastic waste both result in similar CO_2 emissions. The study shows that CO_2 emissions strongly depend on the material losses after the sorting plant and the product quality of the secondary plastics. The specific application of mechanical recycling determines whether one ends up with lower CO_2 emissions compared to chemical recycling.



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