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Optimized life cycle for plastics, the role of chemical recycling

RISE Research Institutes of Sweden AB**System Transition and Service Innovation - Resources from Waste**

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List of abbreviations

ABS – acrylonitrile-butadiene-styrene
ADP – abiotic depletion potential
AP – acidification potential
CCS – carbon capture with permanent storage
CCU – carbon capture and utilization
CO ₂ – carbon dioxide
EF – environmental footprint
EP – eutrophication potential
EVA – ethylene-vinyl acetate
FRP – fiber reinforced plastics
FU – functional unit

GWP – global warming potential

H₂ – hydrogen gas

HDPE – high-density polyethylene

HIPS – high impact polystyrene

HTL – hydrothermal liquefaction

IPCC – Intergovernmental Panel on Climate Change

IPCC AR5 – Intergovernmental Panel on Climate Change, the Fifth Assessment Report

ILCD – International Reference Life Cycle Data System

LCA – life cycle assessment

LCI – life cycle inventory

LCIA – life cycle impact assessment

MPW – municipal plastic waste

NO_x – nitrogen oxides

ODP - Ozone Depletion Potential

PA – polyamide

PBT – poly(butylene terephthalate)

PC – polycarbonate

PE – polyethylene

PET – poly(ethylene terephthalate)

PLA – poly(lactic acid)

PLLA – poly(L-lactic acid)

PMMA – poly(methyl methacrylate)

POCP – photochemical ozone creation potential

PP – polypropylene

PP-GF – glass fibre reinforced polypropylene

PPE – poly(phenylene ether)

PS – polystyrene

PU – polyurethane

PVC – poly(vinyl chloride)

SAN – styrene-acrylonitrile resin

SO₂ - sulphur dioxide

TRL – technology readiness level

WEEE – waste electrical and electronic equipment

Executive Summary

A cornerstone in the fight against climate change is limiting our consumption of fossil resources by replacing fossil carbon with renewable carbon that comes from biomass, CO₂ and recycling. Chemical recycling is therefore seen as one of the most important steps towards a renewable carbon economy as it converts waste plastics into a renewable carbon source for the chemical and polymer industry. Through chemical recycling, plastic and other polymer-based materials become incorporated into the carbon cycle, which makes the polymers circular and carbon-sustainable.

The objective of this project is to support investors, policy makers and industry in Norway and Europe in understanding the environmental potential of various chemical methods for recycling plastic waste. This is by creating a reliable approach to the multifaceted assessment of such potential by means of LCA, as well as an understanding of the objective factors currently preventing its accurate assessment.

To make the assessment as robust as possible in the face of existing uncertainties, the project uses a simplified approach and assess the potential of several major technologies with middle to high current TRL levels. The assessment is made for several widely used types of polymers most suitable for processing by these methods. The analysis is carried out for:

1. Gasification of all plastic waste that is not mechanically recycled in a) Norway and b) Europe in 2030.
2. HTL of all plastic packaging waste that is not mechanically recycled in a) Norway and b) Europe in 2030.
3. Pyrolysis of all polyolefins (PE and PP) and PS that are not mechanically recycled in Europe in 2030.
4. Depolymerization (glycolysis) of all PET that is not recycled mechanically recycled in Europe in 2030
5. Gasification of all plastic waste that is not mechanically recycled in a) Norway and in b) Europe in 2050

Based on the assessment made it can be concluded that all chemical recycling options have advantages compared to incineration in terms of CO₂-equivalents per functional unit. Even though pyrolysis and HTL options result in net release of atmospheric emissions, they still outperform incineration by almost an order of magnitude. The same ratio is demonstrated in the analysis of gasification vs incineration in 2050. It is anticipated though that the development of new technologies, such as CCS/CCU, may affect the result of this long-run assessment.

While CCS/CCU technologies may revolutionize our understanding of key criteria for environmental impact assessment, resource utilization has the potential to emerge as a central criterion in our pursuit of sustainability.

Introduction

The objective of this project is to support investors, policy makers and industry in Norway and Europe in understanding the environmental potential of various chemical methods for recycling plastic waste. This is by creating a reliable approach to the multifaceted assessment of such potential as well as an understanding of the objective factors currently preventing its accurate assessment.

The project attempts to address these issues in a very dynamic situation linked to the development of chemical recycling. Such high dynamics is associated both with changes in the understanding of the role and importance of chemical recycling, and with the explosive

development in related fields that can affect environmental balance of the recycling technologies (such as CCU), and the recycling methods themselves. The report attempts to avoid being tied to a static picture and provide an analysis that takes into account the dynamics of development. At the same time, attention is paid to clarifying the differences in the description of the situation given in the report at the moment, and the project proposal two years ago.

Chemical recycling, current state

A cornerstone in the fight against climate change is limiting our consumption of fossil resources by replacing fossil carbon with renewable carbon that comes from biomass, CO₂ and recycling¹. Chemical recycling is therefore seen as one of the most important steps towards a renewable carbon economy as it converts waste plastics into a renewable carbon source for the chemical and polymer industry and ensures that the carbon stays within the anthroposphere instead of being emitted to the atmosphere. Through chemical recycling, plastic and other polymer-based materials become incorporated into the carbon cycle, which makes the polymers circular and carbon-sustainable.

In addition, a modern, sustainable plastics industry that fits into a circular economy cannot do without chemical recycling because the objectives of the EU plastics strategy cannot be achieved without the implementation of chemical recycling technologies². As it was calculated before amendments to the EU Packaging and Packaging Waste Directive made in 2018, to achieve a 50 percent reuse and recycling rate by 2030, 75 million tons of plastic waste needs to be chemically recycled. Capital investments of \$ 15 to \$ 20 billion per year will be needed to reach sufficient chemical recycling capacity.³ Current target set in the Directive is 55%⁴. Yet despite substantial interest in investment in this sector, data to underpin such potential investments is based on limited commercial-scale developments for established technologies such as pyrolysis, and scale-up assumptions from lower TRL emerging technology pilots. Moreover, policy makers need clear evidence upon which to set out their approach to market and environmental regulation for this nascent industrial sector. This necessitates the creation of large-scale pilots to produce broad data sets around the economics, deliverability and the environmental performance of chemical recycling technologies, in order to reduce commercial risk and facilitate future sustainable investments. Such projects are being actively implemented at present⁵.

Ongoing pioneering projects are developing various chemical recycling technologies. These technologies differ by the degree of polymer degradation, by their selectivity in raw materials and tolerance to contaminants, process parameters (temperature, medium, pressure) and thus capital and operating costs. In addition, the products of these plastic processing techniques differ in their post-processing requirements, making the situation even more complicated. A brief overview of the processes used for chemical recycling of polymers is given in Table 1.

¹ According to the definition of "renewable carbon" by the Renewable Carbon Initiative <http://www.renewable-carbon-initiative.com>

² Chemical Recycling – Status, Trends, and Challenges – Technologies, Sustainability, Policy and Key Players, nova-Institute, 2020

³ How plastics waste recycling could transform the chemical industry, McKinsey, 2018

⁴ <https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vkq1820tqoz1>

⁵ For example, companies such as Quantafuel (Norway), Fuenix Ecology (Netherlands), and Mura Technology (UK)

REPORT

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Table 1 An overview of various chemical recycling processes

Technology	Advantages	Disadvantages	Input material/ types of polymers	Relevant flows	Product
Depolymerization (chemolysis)	Ideal chemical recycling with minimal decomposition allowing to obtain virgin properties. Pure value-added products, lower energy consumption compared to other chemical recycling technologies. Naturally integrated into polymer production lines.	Only homogeneous flows of polyamides, polyesters, and nylons can be processed	PET, PU, PC, PA, PLA, PLLA	PET, PA and PC packaging; PU and PA from the automotive and houseware	Monomers
Pyrolysis	Flexible process suitable to polymers that are difficult to depolymerize and for mixed plastics	Complexity or reactions, sensitivity to feedstock quality, high energy consumption, low tolerance to PVC	PE, PP, PMMA, PS, HIPS, ABS, PU, mixed PE/PP/PS, FRP composites, multi-layered plastics	Packaging, automotive (excl. PVC), construction (excl. PVC), partly agriculture and WEEE	Mixed hydrocarbons, require further processing

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HTL/supercritical water	Flexible process suitable for mixed plastics, tolerates high moisture content and organic contaminants in the feedstock	High energy consumption	PE, PP, PET and PS, mixed and multi-layered plastics	Packaging	Naphtha and heavy wax residue, requires further processing
Gasification	Well-established technology with versatile product, suitable for mixed plastic waste	Requires extremely high feedstock volumes to be feasible. Cost and energy intensive	All types of plastics, mixed plastics	All	Syngas, requires further processing

It is important to note that there are many modifications of the methods mentioned in the table above, which can differ significantly from each other both in terms of process parameters and the level of development at the present time, see Table 2 below.

Table 2 Technical parameters and current state of operation for specific chemical recycling processes

Process	Process parameters	Input	Output	TRL
Depolymerization (chemolysis)				
Hydrolysis	T: 70 – 350 °C p: high agent: water, steam Long process time	PET, PU, PC, PA, PLA, PLLA	Monomers, yield 70 – 100%	TRL 7 for polyesters ⁶
Glycolysis	T: 160 – 275 °C p: 0.1–0.6 MPa agent: glycols process time: 0.5–8 h microwave heating for PC	PET, PU, PC	Monomers, yield up to 99 % for PET, 80 – 95 % for PU, 50 – 80 % for PC	TRL 9 for PET ⁷

⁶ Companies such as Gr3n <https://gr3n-recycling.com/technology.html>, Carbios <https://www.carbios.com/en/carbios-pursues-its-genuine-revolution-in-the-biorecycling-of-pet-based-plastics/>, and Aquafil <https://www.aquafileng.com/en/polymer-plants/polyester/recycling/>

⁷ For example such companies as Ioniqa <https://ioniqa.com/> and PerPETual <https://www.perpetual-global.com/manufacturing/companies>

Alcoholysis	T: 300 for PET, 200 for PC p: high (sub- and supercritical conditions), agent: alcohols (ethanol, butanol, pentaerythrol, isooctyl alcohol)	PET, PC	Monomers, yield for PET up to 100 %	TRL 4 ⁸
Methanolysis	T: 160 – 300 °C p: 2–4 MPa agent: methanol in ionic liquids	PET, PU, PC, PLA, PLLA	Monomers, yield 90 – 95 %	TRL 8 for polyesters ⁹
Aminolysis	T: 100 – 220 °C p: 2 MPa agent: amines	PET, PU, PC	Monomers, yield 75 – 80 %	TRL 4 ¹⁰
Pyrolysis				
Thermal (conventional) pyrolysis	T: 400 – 900 °C inert atmosphere	Polyolefins, PS, PMMA, PTFE	mixed hydrocarbons: C1-C50	TRL 9 ¹¹
Catalytic pyrolysis	T: 300 – 500 °C catalyst: zeolites, silica, aluminas	PE, PP, PS	mixed hydrocarbons: C3-C4 olefins, C4-C5 isoparaffins, gas, liquid fuel, tar	TRL 9 ¹¹
Microwave assisted pyrolysis	up to 1000 °C	Mixed plastics except PVC	mixed hydrocarbons	TRL 4 ¹¹
Plasma pyrolysis	T: 1730 to 9730 °C process time: 0.01 to 0.5 sec	Mixed plastics except PVC	mainly CO and H ₂	TRL 4 ¹¹

⁸ Janusz Datta & Patrycja Kopczyńska (2016) From polymer waste to potential main industrial products: Actual state of recycling and recovering, Critical Reviews in Environmental Science and Technology, 46:10, 905-946, DOI: 10.1080/10643389.2016.1180227

⁹ <https://www.loopindustries.com/en>

¹⁰ Janusz Datta & Patrycja Kopczyńska (2016) From polymer waste to potential main industrial products: Actual state of recycling and recovering, Critical Reviews in Environmental Science and Technology, 46:10, 905-946, DOI: 10.1080/10643389.2016.1180227

¹¹ Martyna Solis and Semida Silveira (2020) Technologies for chemical recycling of household plastics – A technical review and TRL assessment, Waste Management 105 (2020) 128–138

Pyrolysis with in-line reforming	T: 500-900°C two-stage	Mixed plastics except PVC	mixed hydrocarbons, H ₂	TRL 4 ¹¹
Hydrocracking	T: 350 – 500 °C hydrogen atmosphere (70atm)	Mixed plastics except PVC	oil and gas, liquid fuel	TRL 7 ¹¹
Gasification				
Conventional gasification	T: 700 – 1200 °C gasifying agent: air, steam or oxygen	Mixed plastics	syngas and mixture of hydrocarbons	TRL 9 ¹¹
Plasma gasification	T: up to 14,000 °C plasma gas and steam	Mixed plastics	syngas and mixture of hydrocarbons	TRL 9 for hazardous waste ¹¹

Optimized life cycle for plastics, the role of chemical recycling

LCA as an important instrument for understanding the development priorities

Navigating through the abovementioned technical possibilities requires tools, of which the LCA is of the greatest interest. Comparing different plastic recycling options with LCA and thus creating an understanding of the industry's development priorities looks like an attractive approach. Therefore a large number of new LCA studies in this area are published continuously. In addition to LCA reports mentioned in the project proposal, several notable new papers have been published in 2020 and 2021^{12,13,14}. Some of them are limited to analyzing the potential of one technology for one or several types of polymers, others, like studies published by Schwarz et al. and Meys et al., try to cover a large number of plastics and modifications of chemical processing technologies.

It is important to understand, though, that all these analyzes are carried out in the face of significant data gaps and large uncertainties. This is not only due to the already mentioned need to rely on scale assumptions from pilots with lower TRLs, but also due to uncertainties related to the logistical and organizational inadequacy of the resource management system for the circular economic model and chemical recycling as part of it. To circumvent these uncertainties, assumptions are made on which the analysis is based. These assumptions can subsequently significantly affect the study's results, interpretation and conclusions. For example, the study published by Meys et al.¹⁴ disregards the fact that sorting requirements differ markedly for different technologies, and that different processes require different scaling to be economically acceptable, which should be reflected in the difference in logistics costs. In addition, the analysis in this work is based on the assumption of "thermodynamically ideal chemical recycling", which can lead to erroneous conclusions. This limits the value of such an analysis mainly to a theoretical assessment from above. The study published by Schwarz et al.¹³ also attempts to assess the impact of several chemical technologies and all major plastics

¹² Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., & Azapagic, A. (2021). Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. *Science of The Total Environment*, 769, 144483

¹³ Schwarz, A. E., Ligthart, T. N., Bizarro, D. G., De Wild, P., Vreugdenhil, B., & van Harmelen, T. (2021). Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Management*, 121, 331-342

¹⁴ Meys, R., Frick, F., Westhues, S., Sternberg, A., Klankermayer, J., & Bardow, A. (2020). Towards a circular economy for plastic packaging wastes—the environmental potential of chemical recycling. *Resources, Conservation and Recycling*, 162, 105010

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using a theoretical matrix model that assumes pure polymers as waste input. However, to test applicability of the model to existing plastic recycling challenges, a system boundary extension is added to quantify the impact of several important steps in the plastic production and recycling chain for two pilot waste streams. Such testing leads the researchers to conclude that the inclusion of sorting and cleaning in the model has the most significant impact on LCA results for certain types of plastics. This illustrates that system parameters cannot be neglected for a correct LCA assessment.

This project has an ambition to provide practical support in evaluating the potential of various chemical recycling processes for real polymer material flows. That is why aspects such as logistics, sorting/pre-processing, etc. are an important part of the LCA model developed within this project. In addition, an attempt is made to take into account the potential of emerging technologies and system improvements in long-term evaluations.

Norwegian and European waste plastics statistics in the light of the application of chemical recycling

The annual amount of plastic waste generated in Norway is estimated as 540,000 tons¹⁵. The corresponding amount for Europe is about 29,500,000 tons¹⁶. Of this amount in Norway, 24% or 140,000 tons go to mechanical recycling. In Europe, 34.6% or 10,200,000 tons are sent to recycling facilities. Other plastic waste is sent to incineration or landfill and can be considered as a potential feedstock for chemical recycling technologies. Also, a rather significant part of the material sent to mechanical recycling is sorted out as reject and is not recycled mechanically. This reject from mechanical recycling is also a candidate to be processed through chemical recycling methods with low sensitivity to the input material quality, such as gasification, for example. The actual amount of mechanically recycled plastic in 2021 in Europe is estimated at 23.1%¹⁷

The distribution of Norwegian plastic waste by different product flows is shown in Figure 1.

¹⁵ Mepex Consult AS, Materialstrømmen til plast i Norge – hva vet vi? Report to Handelens Miljøfond, 2020

¹⁶ [Plastics-the-facts-2021](#)

¹⁷ <https://packagingeurope.com/news/european-plastic-mechanical-recycling-rate-at-23-says-ami/7933.article>

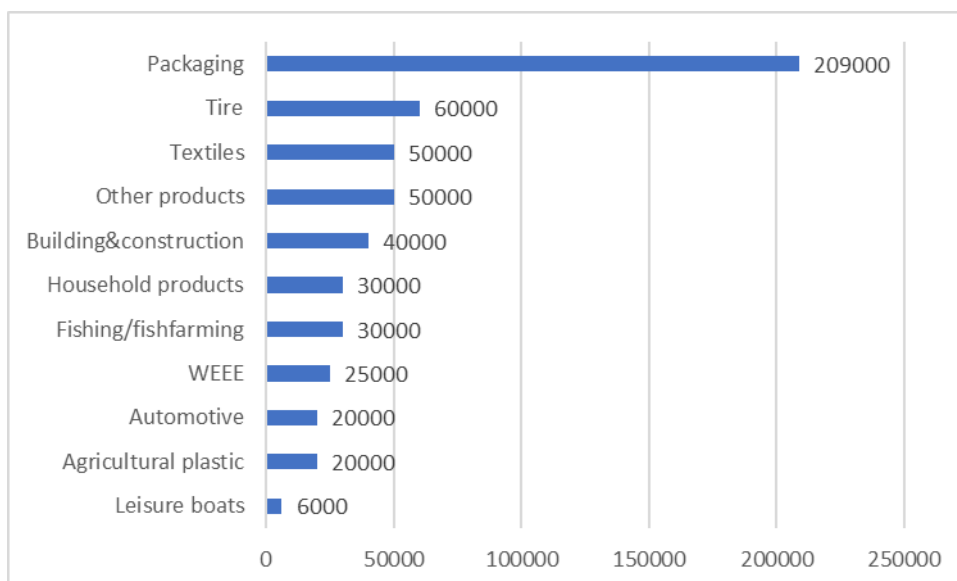


Figure 1 Estimated amount of plastic waste in Norway, divided into product categories (tons)¹⁵

The data on plastic waste distribution by product flow available for Europe is shown in Figure 2.

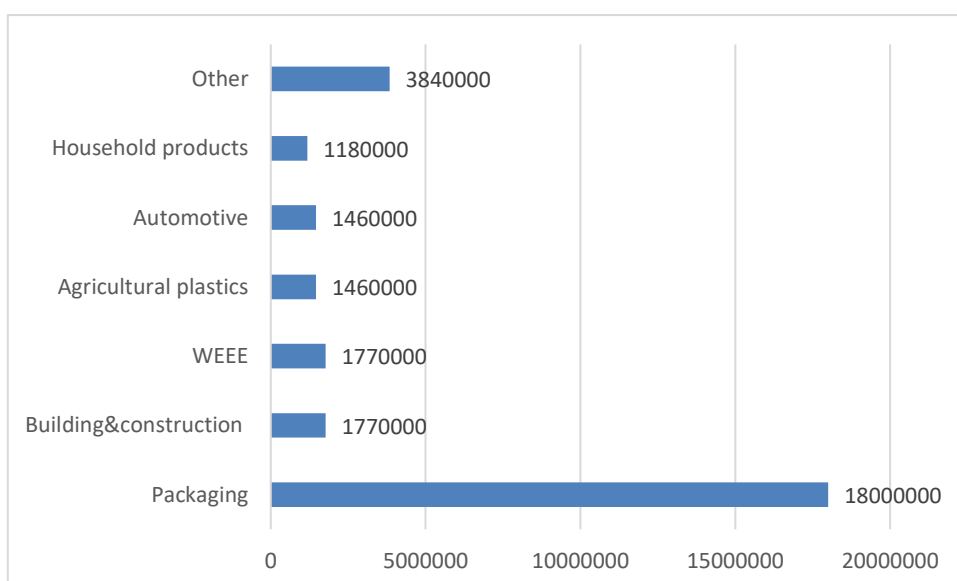


Figure 2 Estimated amount of plastic waste in Europe, divided into product categories (tons)¹⁸

In order to assess the potential of chemical recycling for different streams/categories, it is important to understand (i) what polymers constitute these streams, which will determine the applicable chemical recycling methods, and (ii) what is the share of these streams that remains unrecycled now and thus constitutes a potential raw material for chemical methods.

The typical types of plastics in each plastic waste stream and potentially applicable chemical processing methods are presented in Table 3.

¹⁸ <https://www.statista.com/statistics/986584/distribution-of-plastic-waste-collected-in-europe/>

Table 3 Polymer types present in plastic waste streams and potentially applicable chemical recycling methods

Plastic waste stream	Polymer types represented in the stream	Applicable chemical recycling methods
Packaging	PET, LDPE, HDPE, PP, PS, PVC, rubber, PS/ABS, PA/PBT, PE/PP ^{19, 20}	HTL, Pyrolysis excl. PVC Gasification
Tire	rubber	Pyrolysis Gasification
Textiles	polyester, nylon (PA), PMMA ²¹	Depolymerization Gasification
Building & construction	ABS, PA, PC, PE, PET, PMMA, PP, PS, PVC ²²	Thorough sorting is required Depolymerization for PA, PC, and PET Pyrolysis excl PVC Gasification
Household products	PP, PVC, PS, PE, ABS, SAN, PMMA, PA, PC ²³	Thorough sorting is required Depolymerization for PA and PC Pyrolysis excl PVC Gasification
WEEE	PC, PP, ABS, HIPS, PS, PA, PVC, PBT, PPE ²⁴	Thorough sorting is required Depolymerization for PA and PC Pyrolysis excl PVC Gasification
Automotive	PE, PP, PC, ABS, PVC, rubber, PU, synthetic fabrics ²⁵	Pyrolysis for PE, PP, ABS and rubber Depolymerization for PC and PU Gasification
Agricultural	PE, LDPE, EVA, PP, PVC ^{26, 27}	Pyrolysis excl PVC, HTL Gasification

¹⁹ Meys, R. et al., Towards a circular economy for plastic packaging wastes – the environmental potential of chemical recycling, 2020, Resour. Conserv. Recycl. 162, 105010.

²⁰ Dahlbo, H. et al. Recycling potential of postconsumer plastic packaging waste in Finland. 2018, Waste Management, 71, 52-61

²¹ <http://polymerdatabase.com/Fibers/Textiles.html>

²² Lahtela, V. et al. Composition of plastic fractions in waste streams: Toward more efficient recycling and utilization. 2019, Polymers, 11(1), 69

²³ [Plastics-the-facts-2021](#)

²⁴ Kousaiti, A. et al. Assessment of tetrabromobisphenol-A (TBBPA) content in plastic waste recovered from WEEE. 2020, Journal of Hazardous Materials, 390, 121641

²⁵ Pilát, P., & Patsch, M. Possibilities of Energy Utilization of Waste from the Automotive Industry at Present. 2020, In MATEC Web of Conferences (Vol. 328). EDP Sciences

²⁶ Vox, G. et al. Mapping of agriculture plastic waste. 2016, Agriculture and Agricultural Science Procedia, 8, 583-591

²⁷ Horodytska, O. et al. Plastic flexible films waste management—A state of art review. 2018 Waste Management, 77, 413-425

Unfortunately, more detailed analysis of waste plastic streams is not possible with today's knowledge base. Information on the proportion of different types of polymers in a stream is not available in most cases. The most complete information about polymer types found in the stream and their post-consumer fate is available for plastic packaging. Therefore, packaging is used as a pilot stream to test the LCA model developed in this project. Since packaging plastic is the most massive flow, it seems reasonable and interesting as a pilot.

Based on a sampling study performed in Norway for two streams of waste plastic packaging: (i) collected separately, and (ii) present in the household waste, the following composition of the streams can be estimated, see Table 4²⁸.

Table 4 Average composition of the waste plastic packaging streams in Norway

Polymer	Share in the separately collected stream	Share in plastics from household waste	Share in the packaging stream, total
PET bottles	4.5%	4.5%	4.5%
HDPE	7.6%	6.2%	6.6%
PP	13.6%	11.9%	12.4%
PE film	39.5%	41.2%	40.7%
PET tray	10.6%	6.8%	7.8%
PS	3%	4%	3.7%
PP film and other film	7.6%	10.2%	9.5%
Other hard plastic packaging	0%	1.7%	1.2%
Black hard plastic packaging	7.6%	6.2%	6.6%
PE laminate	6%	7.3%	7%

Corresponding data at European level is missing. It can be assumed, however, that types of packaging used in different European countries including Norway are similar to a high extent. The only significant difference thus can be expected in the amount of PET bottles ending up in these streams. This is because PET deposit system is not used in all European countries. This means that, if PET bottles make up about 12% of plastic packaging in general^{29, 30}, this amount should be taken into account when considering general European statistics for plastic waste.

Packaging plastic found in the household waste is not suitable for mechanical recycling and is thus a candidate to be recycled chemically. Packaging plastic collected separately is the flow that is sent to sorting and mechanical recycling. Approximately 50% of this material become reject at the sorting facility or in the process of recycling itself and is thus a feedstock for chemical recycling.

A detailed overall assessment of the chemical technology potential in Norway and Europe cannot be made on the basis of currently available data. There is a lot of uncertainty in the analysis of different flows, types of plastics and their amounts and where in the flow they can

²⁸ Mepex Consult AS, Materialstrømmen til plast i Norge – hva vet vi? Report to Handelens Miljøfond, 2020

²⁹ Allerup, J. and. Fråne, A (2016). Sveriges återvinning av förpackningar och tidningar: Uppföljning av producentansvar för förpackningar och tidningar 2015, Naturvårdsverket

³⁰ Nakatania, J. et al., Revealing the intersectoral material flow of plastic containers and packaging in Japan, 2020, PNAS

be found. This is in addition to the uncertainties associated with the need to use scale-up assumptions and adapt the waste management system to circular principles. To make the assessment as robust as possible in the face of such uncertainties, the project uses a simplified approach and assess the potential of several major technologies with middle to high current TRL levels. The assessment is made for several widely used types of polymers most suitable for processing by these methods. This is without a detailed analysis of the streams. In all cases material suited for mechanical recycling is excluded from the consideration.

The analysis is carried out for:

1. **Gasification of all plastic waste that is not mechanically recycled.** It is assumed that by 2030 the amount of plastic waste will reach 750,000 tons/year for Norway and 41,000,000 tons/year for Europe, accompanying the grow of the market³¹. Mechanical recycling rates are assumed to reach 15 %³² and the necessary capacities for processing such amount of waste plastics through gasification are available.
2. **HTL of all plastic packaging waste that is not mechanically recycled.** It is assumed that by 2030 the amount of plastic packaging waste will reach 300,000 tons/year for Norway and 25,800,000 tons/year for Europe, accompanying the grow of the market³³. The mechanical recycling rate for plastic packaging is assumed to reach 36%³⁴. It is also assumed that the necessary capacities for processing such amount of waste plastics through HTL are available.
3. **Pyrolysis of all polyolefins (PE and PP) and PS that are not mechanically recycled**³⁵. It is assumed that by 2030 the amount of PE waste in Europe will reach 18,200,000 tons/year, PP waste 9,700,000 tons/year, and PS waste 3,420,000 tons/year. These estimations are made from below and take into account an average lifetime of products made of PE/PP/PS³⁶, current market demand³⁷ for PE/PP/PS and the expected market growth rate^{38, 39}. 5,200,000 tons PE and 2,400,000 tons PP are estimated to be mechanically recycled annually at that time. These numbers are calculated from the amount of plastic packaging waste in Europe that reaches 24,500,000 tons in 2030⁴⁰, and the assumption that the recycling rate for plastic packaging will double by 2030.
4. **Depolymerization (glycolysis) of all PET that is not recycled mechanically**³⁵. It is assumed that by 2030 the amount of PET waste in Europe will reach 6,900,000 tons. This estimations is based on average lifetime of products made of PET⁴¹, current

³¹ [Plastic Market Size, Share & Trends Analysis Report By Product \(PE, PP, PU, PVC, PET, Polystyrene, ABS, PBT, PPO, Epoxy Polymers, LCP, PC, Polyamide\), By Application, By End Use, And Segment Forecasts, 2022 - 2030](#)

³² Hundertmark, T. et al, How plastics waste recycling could transform the chemical industry, 2018, McKinsey&Company

³³ <https://www.transparencymarketresearch.com/europe-plastic-packaging-market.html>

³⁴ <https://packagingeurope.com/news/european-plastic-mechanical-recycling-rate-at-23-says-ami/7933.article>

³⁵ Please note that due to the lack of relevant data such analysis cannot be performed for Norway

³⁶ <https://ourworldindata.org/grapher/mean-product-lifetime-plastic>

³⁷ [Plastics-the-facts-2021](#)

³⁸ <https://www.fortunebusinessinsights.com/industry-reports/polyethylene-pe-market-101584>

³⁹ [https://www.marketwatch.com/press-release/polystyrene-ps-market-size-by-consumption-analysis-developments-and-trends-growth-forecast-regions-type-manufacturers-and-application-2022-05-11#:~:text=The%20global%20Polystyrene%20\(PS\)%20market%20size%20is%20projected%20to%20reach,2.3%25%20during%202021%2D2026.](https://www.marketwatch.com/press-release/polystyrene-ps-market-size-by-consumption-analysis-developments-and-trends-growth-forecast-regions-type-manufacturers-and-application-2022-05-11#:~:text=The%20global%20Polystyrene%20(PS)%20market%20size%20is%20projected%20to%20reach,2.3%25%20during%202021%2D2026.)

⁴⁰ <https://www.mordorintelligence.com/industry-reports/plastic-packaging-market>

⁴¹ <https://ourworldindata.org/grapher/mean-product-lifetime-plastic>

market demand⁴² for PET and the expected market growth rate⁴³. The recycling rate for PET is expected to double and reach 58%⁴⁴.

No data is available to make any reasonable assumptions about the amount of plastic waste in Norway or Europe by 2050. WWF estimates that global plastic production will triple by then⁴⁵. To estimate the amount of plastic waste in Norway and Europe based solely on this assumption does not seem reasonable, first of all as the largest growth in demand in the world takes place at the expense of developing countries and regions, but also because too many aspects can affect the structure of the market for plastics and the fate of the newly produced plastic in such a distant future.

However, the analysis of chemical recycling of waste plastics **in 2050** is of particular interest for this study, as it may provide an opportunity to analyze the impact of some important and interesting systemic trends. Hence, an exercise is made in the project where **gasification of all plastic waste that is not recycled mechanically** is analyzed with the amount of plastic waste estimated based on a conservative scenario. Such a scenario predicts that the amount of plastic waste will increase 3.2 times by 2050 and reach a shocking level of 1,728,000 tons in Norway and 94,400,000 tons in Europe. Mechanical recycling is projected to plateau at 14-22% by 2050⁴⁶. Following trends are taken into account:

1. All fuels are fossil free by 2050, meeting the goal of carbon neutrality⁴⁷, which supports green logistics.
2. Standardization of plastics' use and improved design for recycling reduce the cost of sorting (25% reduction in energy consumption is assumed).
3. Up to 100% of plastics are made from renewable resources (bio-based plastics)⁴⁸.

LCA study

Method and data

Life cycle assessment (LCA) is a widely used tool by which the environmental impacts associated with products and services could be assessed over their life cycle stages. The life cycle stages could encompass raw material acquisition/extraction through processing, manufacture, distribution, use, repair and maintenance, to re-use, recycling and disposal, see Figure 3. LCA involves the compilation and evaluation of the inputs and outputs as well as potential environmental impacts i.e. emissions to air, water, soil and energy and material resources associated with a product system throughout its life cycle.

⁴² [Plastics-the-facts-2021](#)

⁴³ <https://www.transparencymarketresearch.com/pet-polyethylene-terephthalate-and-pet-packaging-market.html>

⁴⁴ <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data>

⁴⁵ <https://www.wwf.org.au/news/blogs/plastic-waste-and-climate-change-whats-the-connection#gs.4gz41>

⁴⁶ Toloken, S. Study: Chemical recycling may need decades to be 'low cost', November 03, 2021, Plastics News

⁴⁷ https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en

⁴⁸ <https://nachhaltigwirtschaften.at/en/projects/biobased-plastics-scenario-2050.php>

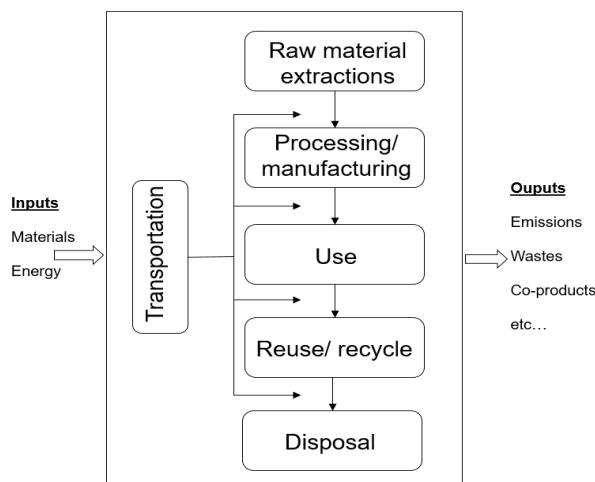


Figure 3 Typical life cycle stages of a product with related input-output activities

The life cycle-based methodology is thus applied in this study to evaluate the environmental implications of end of life management options of different plastic waste flows. The LCA is generally performed according to the general framework (Figure 4) and guidelines for conducting LCA of goods and services as described in the ISO 14040:2006a⁴⁹ and 14044:2006b⁵⁰ standards (ISO 2006a; ISO 2006b) as well as the international Reference Life Cycle Data System (ILCD) Handbook (EC – JCR, 2010).

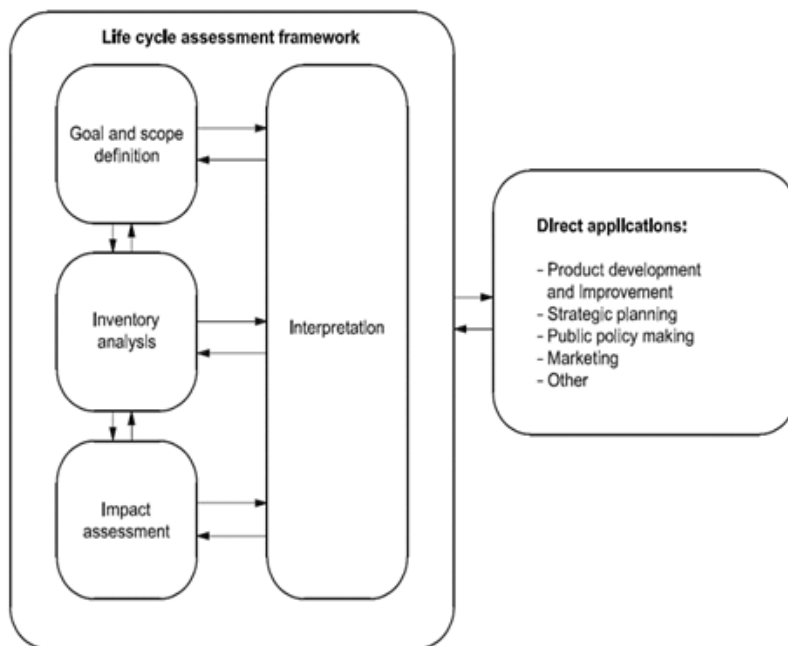


Figure 4 LCA general framework based on ISO 14040

⁴⁹ ISO 2006a. (International Organization for Standardization), ISO 14040 International Standard. Environmental management - Life cycle assessment - Principles and framework. 2006: Geneva, Switzerland.

⁵⁰ ISO 2006b. (International Organization for Standardization), ISO 14044 International Standard. Environmental management - Life cycle assessment - Requirements and guidelines. 2006: Geneva, Switzerland.

The EU provides further guidance on application of the LCA approach to waste management systems (European Commission Joint Research Centre, 2011). ISO 14040 defines the four steps in performing an LCA:

- Goal and scope definition, where the objectives are defined and the extent of the study and the functional unit (FU) are set within the boundaries of the system.
- Life cycle inventory (LCI) or Inventory Analysis: In this stage, mass and energy balances are developed and the inputs/outputs of the system are defined.
- Life cycle impact assessment (LCIA): The impact and burdens are evaluated in this stage with a set magnitude and value with the aid of impact indicators.
- Life cycle interpretation: This is the final stage where the study is systematically evaluated and conclusions with respect to scope and FU are derived.

Studied plastic waste flows

The LCA in this study is performed for estimated plastic waste streams based on different polymer types and their suitability for specific chemical recycling options as described above:

Case 1 Gasification of all plastic waste that is not mechanically recycled in a) Norway and b) Europe in 2030.

Case 2 HTL of all plastic packaging waste that is not mechanically recycled in a) Norway and b) Europe in 2030.

Case 3 Pyrolysis of all polyolefins (PE and PP) and PS that are not mechanically recycled in Europe in 2030.

Case 4 Depolymerization (glycolysis) of all PET that is not recycled mechanically recycled in Europe in 2030

Case 5 Gasification of all plastic waste that is not mechanically recycled in a) Norway and in b) Europe in 2050

For the detailed description of waste flow and specific cases please see the section “Norwegian and European waste plastics statistics in the light of the application of chemical recycling”.

Functional unit

The functional unit in the study is defined as the amount of plastic waste that is not mechanically recycled or recyclable but suitable for recycling based on various chemical recycling techniques. This amount varies for different waste stream depending on the considered geographic (Norway or Europe) and temporal (2030 or 2050) scope.

System boundary

In this analysis, end of life management options for plastic wastes is the focus, thus the system boundary begins with the point at which the different types of plastic wastes are generated, and the impacts associated with the actual production and use of the plastic materials are not covered. The collection, transport, sorting and pre-treatment of the wastes as well as the chemical recycling processes to transform the wastes into useful recycled products that can be used as raw material inputs for similar products or other resources are taken into account. The processes to convert the obtained recycled products from chemical recycling into new materials or products are beyond the defined system boundary.

Life cycle impact assessment

The life cycle impact assessment (LCIA) is based on the environmental footprint (EF) methodology with focus on the following impact categories:

- global warming potential (GWP) as indicator for greenhouse gas effect
- resource use as indicator for natural resource depletion
- acidification potential (AP) as indicator for acid rain phenomenon
- photochemical ozone creation potential (POCP) as indicator for photo-smog creation
- eutrophication potential (EP) as indicator for over fertilization of water and soil

Table 5 Set of used impact categories

Impact category	Description
Acidification	Acidification potential refers to the compounds that are precursors to acid rain (SO ₂ , NO _x). The acidification potential is calculated in SO ₂ -eq.
Climate Change	Global Warming Potential 100 years, based on IPCC AR5 including climate carbon feedback
Climate Change (fossil)	This is a subset of the total Climate Change covering the fossil-related part of the climate change, which adds up to the main climate change impact.
Eutrophication freshwater	Phosphorus equivalents: The degree to which the emitted nutrients reach the freshwater end compartment (phosphorus considered as limiting factor in freshwater)
Eutrophication marine	Nitrogen equivalents: The degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water).
Eutrophication terrestrial	Accumulated Exceedance. The change in critical load exceedance of the sensitive area.
Ozone Depletion	Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.
Photochemical ozone formation	Expression of the potential contribution to photochemical ozone formation. Tropospheric ozone concentration increases as NO _x equivalents
Resource use, fossil	Abiotic resource depletion fossil fuels (ADP-fossil)
Resource use, mineral and metals	Abiotic resource depletion (ADP ultimate reserve).

Life cycle inventory and modelling

Environmental data on materials, fuels and emissions was obtained from the ecoinvent 3.8 database⁵¹. As much as possible, the data from ecoinvent was chosen and where necessary adjusted to reflect the geographical coverage of Norway and Europe. Data for the collection, transport and pre-treatment of the plastic wastes was generally based on ecoinvent processes and estimated transport distances based on a Norwegian study⁵², where waste was assumed to be transported to various destination in the EU for treatment and mechanical recycling. Data for the various chemical recycling processes is very limited and not fully or transparently reported in the few available literature. Still data used for the chemical processes analysed here was mainly obtained based on literature and published technical reports and adjusted where necessary for the context of this study. Input data for the pyrolysis and gasification processes were based on a study by (Lassesson et al., 2021)⁵³, while the emissions were modelled based on (Khoo, 2019)⁵⁴. For HTL, the input data for the processes was recalculated and adjusted for the relevant plastic waste streams based on a study on HTL of microalgae⁵⁵ and (Seshasayee and Savage, 2020)⁵⁶. Depolymerisation is assumed to be through glycolysis and the data for the modelling was based on process description from literature^{57,58}. Incineration was modelled based on the ecoinvent processes for municipal incineration of different plastic waste types. The LCA modelling is done with the SimaPro software (version 9.3.0.3).

Results

Incineration vs gasification of all plastic waste not mechanically recycled in Norway and Europe, 2030

Gasification of all the estimated plastic wastes not mechanically recycled in Norway by 2030 seems to give more climate benefits than incineration, see Figure 5. This is mainly due to the higher efficiency of the gasification process and higher benefits (green bars) from the substituted materials. The red bars represent the sorting, transport and pre-treatment as well as the processes for the recycling options. Overall, from the treatment of the estimated 637,500 tons/year of mixed plastic wastes that are not mechanically recycled or recyclable in Norway by 2030, the option of gasifying them saves about 1.34E8 kg CO₂ eq due to avoided virgin material production, while incinerating this waste result in 1.58E9 kg CO₂ eq emissions.

⁵¹ Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. 2016. "The Ecoinvent Database Version 3 (Part I): Overview and Methodology." *The International Journal of Life Cycle Assessment*, 1218–1230.

⁵² Furberg, A., Callewaert, P., and Lyng, K-A. 2022. Life cycle assessment of household plastic treatment in Norway.

⁵³ Lassesson, H., Gottfridsson, M., Nellström, M., Rydberg, T., Josefsson, L., och Cecilia Mattsson, C. 2021. Kemisk återvinning av plast. Teknik, flöden och miljöaspekter.

⁵⁴ Khoo, H. H., 2019. LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore.

⁵⁵ Zhang B., Wu J., Deng Z., Yang C., Cui C., Ding Y. A Comparison of Energy Consumption in Hydrothermal Liquefaction and Pyrolysis of Microalgae. *Tr Ren Energy*, 2017, Vol.3, No.1, 76-85. doi: 10.17737/tre.2017.3.1.0013.

⁵⁶ Seshasayee, M. S. & Savage P. E. Oil from plastic via hydrothermal liquefaction: Production and characterization. *Applied Energy* 278 (2020) 115673.

⁵⁷ Barboza E.S., Lopez D.R., Amico S.C., Ferreira C.A. Determination of a recyclability index for the PET glycolysis. *Resources, Conservation and Recycling* 53 (2009) 122–128.

⁵⁸ Schwarz, A. E., Ligthart, T. N., Bizarro, D. G., De Wild, P., Vreugdenhil, B., & van Harmelen, T. (2021). Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Management*, 121, 331-342.

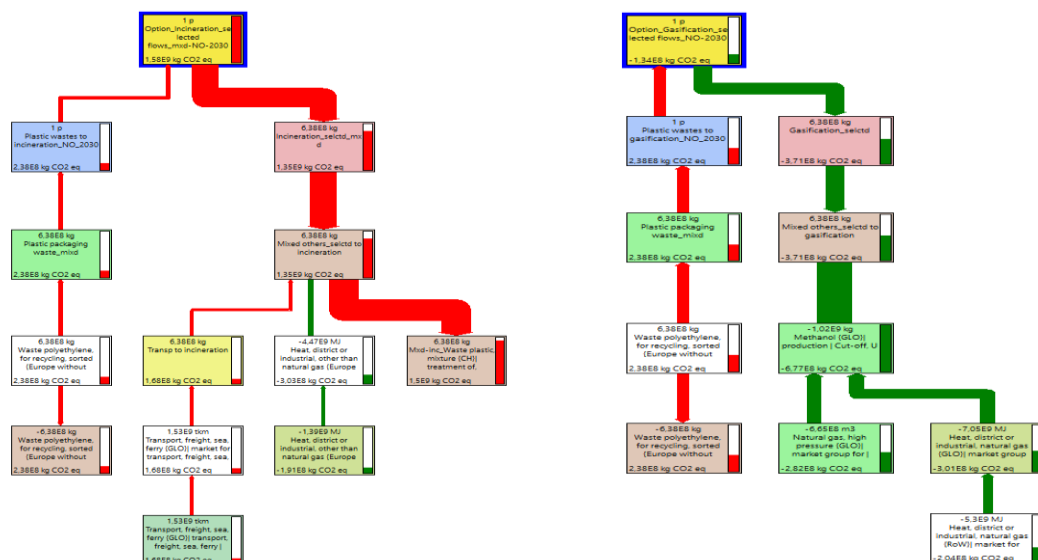


Figure 5 Climate change impact⁵⁹ of incineration (left) and gasification (right) for all plastic wastes not mechanically recycled in Norway, 2030

The characterization results for the selected range of impact categories for the incineration and gasification of all plastic wastes not mechanically recycled in Norway by 2030 are presented in Figure 6. The results are presented in relative percentage terms and show that gasification of the selected plastic waste streams performs better in most of the categories.

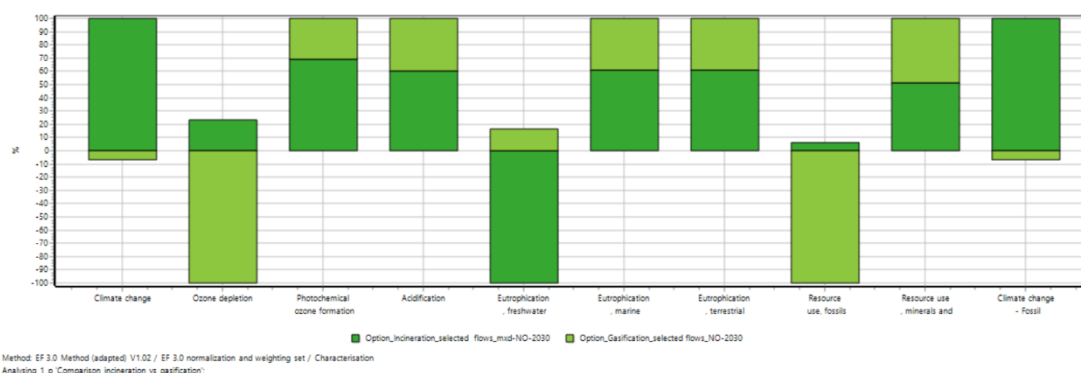


Figure 6 Life cycle impact of incineration and gasification for all plastic wastes not mechanically recycled in Norway, 2030

Similar trends are observed for the incineration and gasification of the estimated non-mechanically recyclable mixed plastic waste streams of 34,850,000 tons/year in Europe (Figure 7), but with a greater magnitude of 7.31E9 kg CO₂ eq emissions savings from gasification compared to 8.66E10 kg CO₂ eq emissions to the atmosphere from incineration.

⁵⁹ Please note that calculation schemes are much more complex and contain many more steps. The schematic diagrams in this report only show the life cycle stages with the highest impact to make them easier to read.

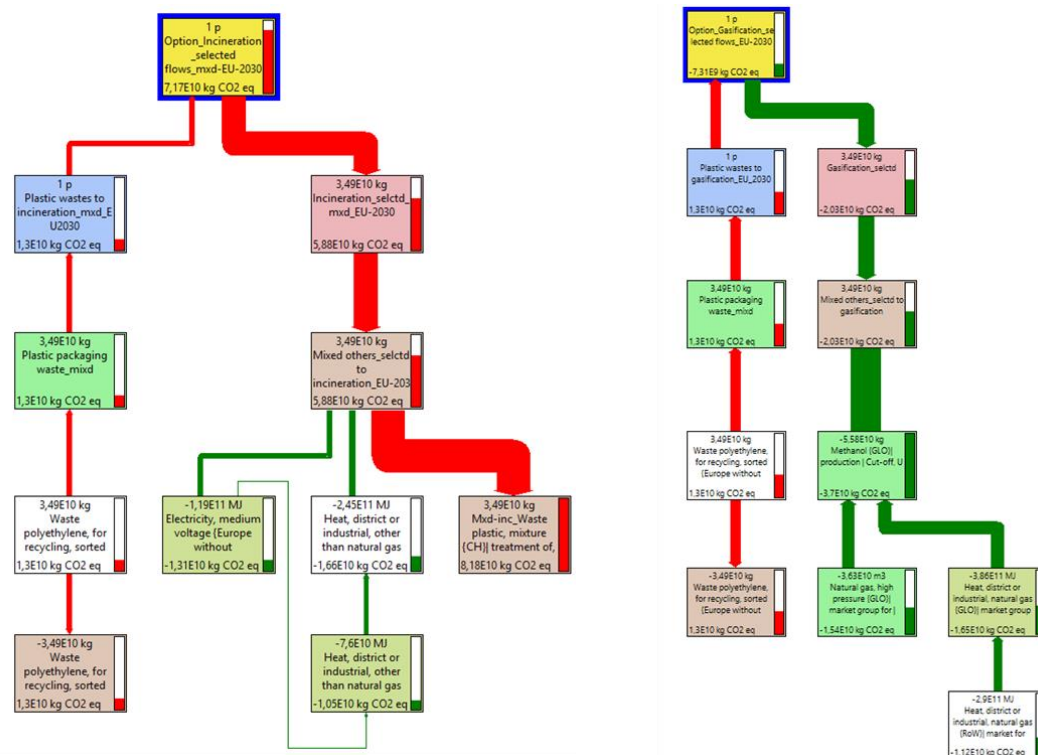


Figure 7 Climate change impact of incineration (left) and gasification (right) for all plastic wastes not mechanically recycled in Europe, 2030

The characterization results for the selected impact categories also follow similar trends, comparing the incineration of all plastic wastes not mechanically recycled in Europe by 2030 with gasification as presented in Figure 8.

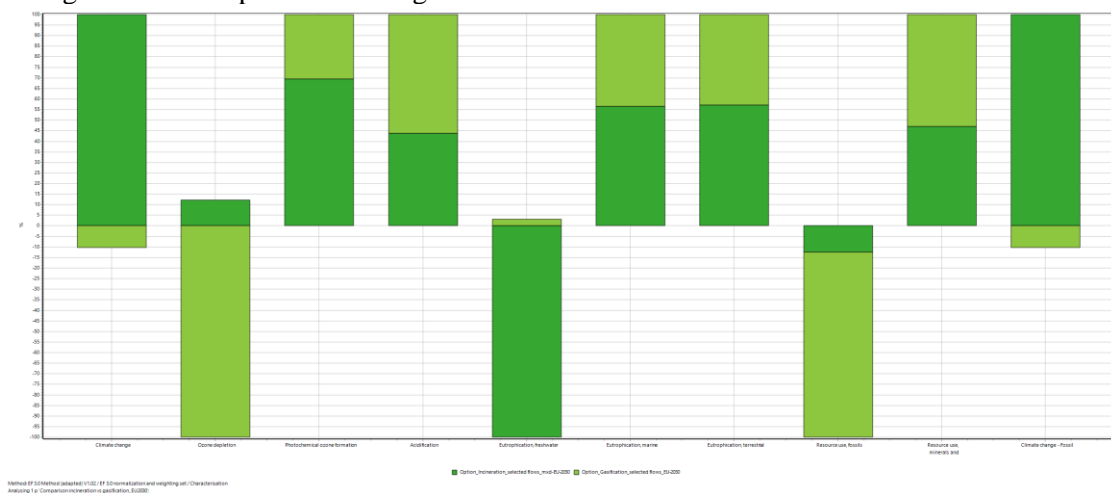


Figure 8 Life cycle impact of incineration and gasification for all plastic wastes not mechanically recycled in Europe, 2030

HTL vs gasification of all plastic packaging waste not mechanically recycled in Norway and Europe in 2030.

HTL of all plastic packaging waste that is not mechanically recycled in Norway by 2030 results in about 3.81E8 kg CO₂ eq less net emissions to the atmosphere compared to the incineration of these waste flows (Figure 9). This can be attributed to the high efficiency as well as larger benefits from the avoided products for the HTL process compared to

incineration. The results for the selected impact categories presented in Figure 10 show that HTL gives better environmental performance than incineration in all the indicators, except for freshwater eutrophication and resource use for minerals and metals. This may be linked to the use of deionized water for the HTL process.

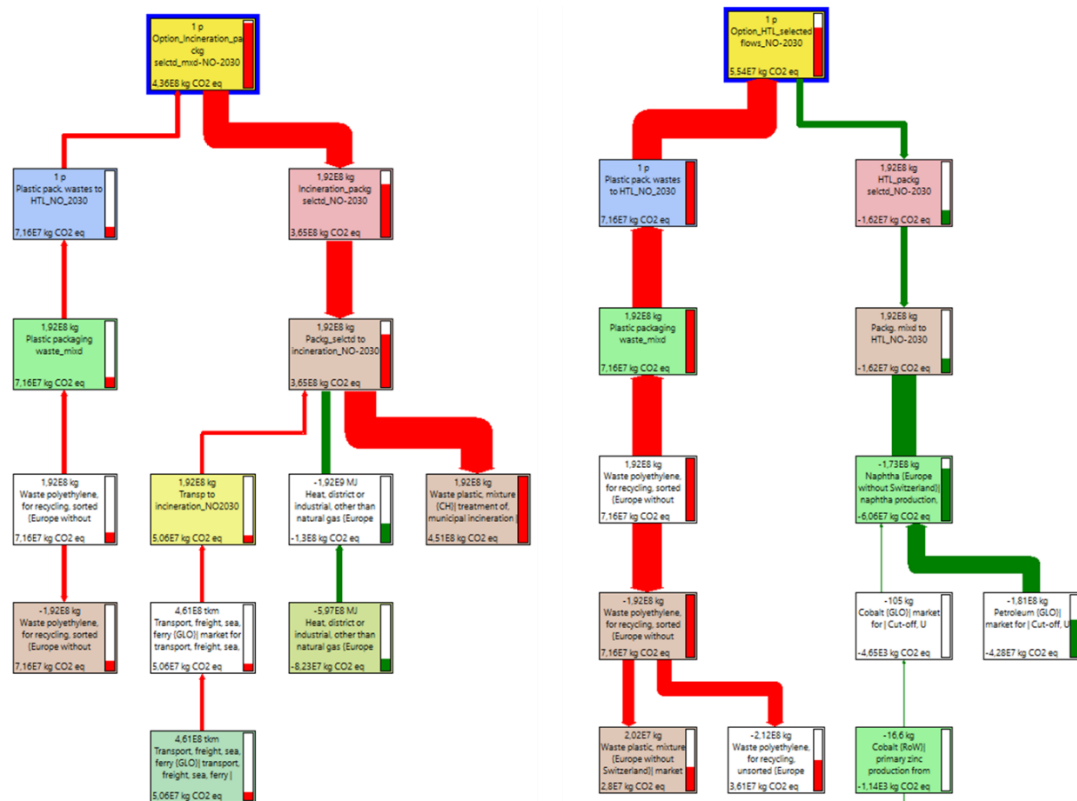


Figure 9 Climate change impact of incineration (left) and HTL (right) for all plastic packaging waste that is not mechanically recycled in Norway, 2030

The characterization results for the selected impact categories HTL of all plastic packaging waste that is not mechanically recycled in Norway by 2030 are presented in Figure 10.

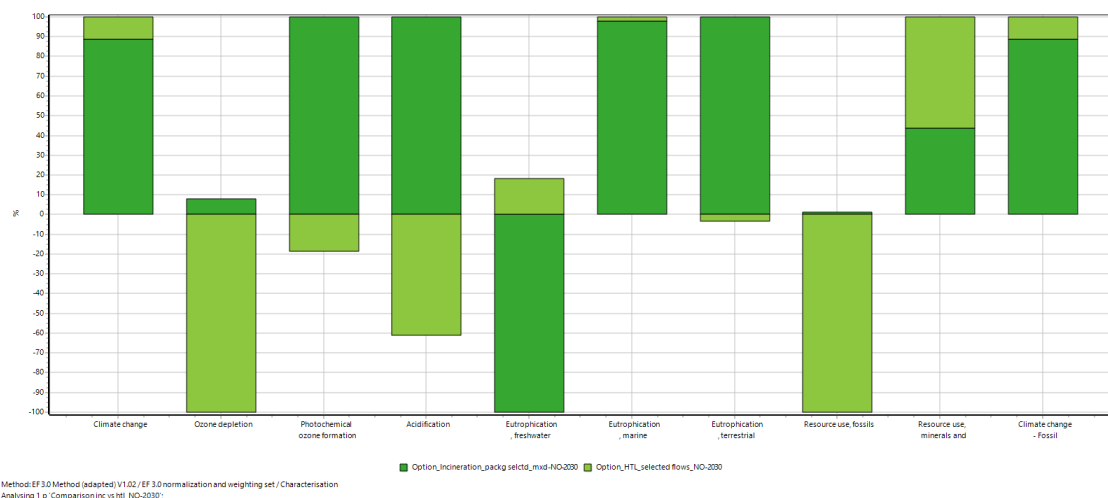


Figure 10 Life cycle impact of incineration and HTL for all plastic packaging waste that is not mechanically recycled in Norway, 2030

Similarly, Figure 11 shows that for the same packaging waste flows at the European level, the emissions due to HTL are about 2.80×10^{10} kg CO₂ eq less than the emissions from incineration. For the selected impacts shown in Figure 12, treatment of the packaging wastes through HTL still performs better, except for freshwater eutrophication and resource use for minerals and metals for similar reasons.

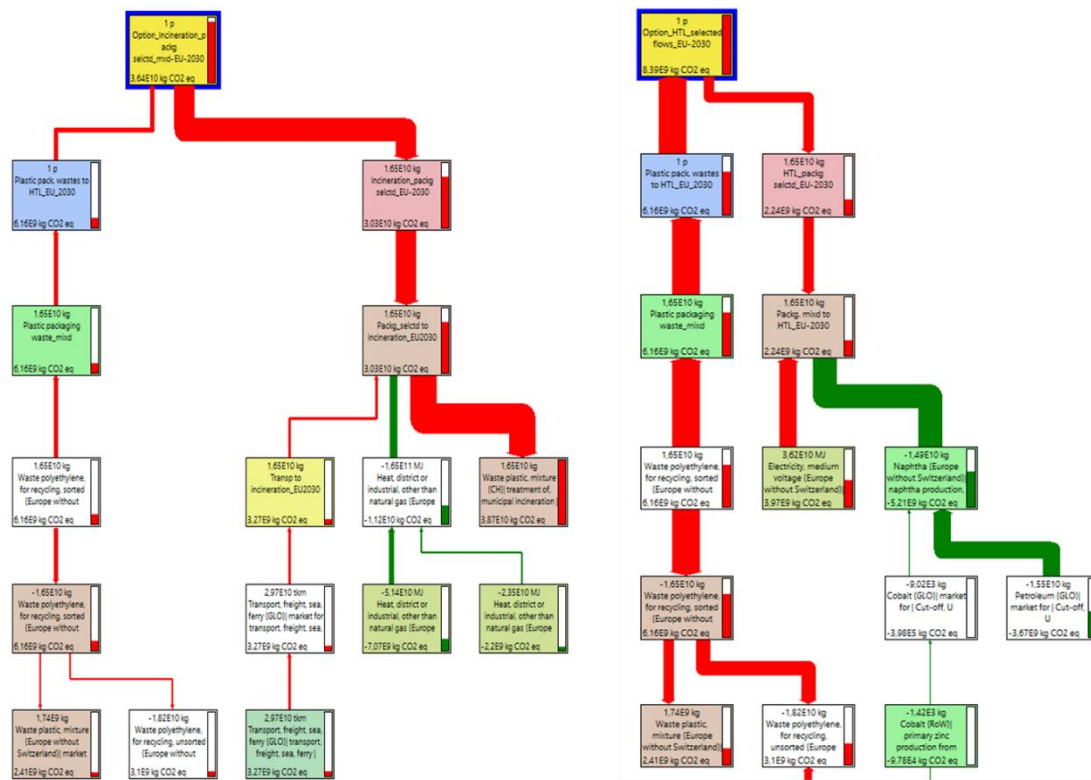


Figure 11 Climate change impact of incineration (left) and HTL (right) for all plastic packaging waste that is not mechanically recycled in Europe, 2030

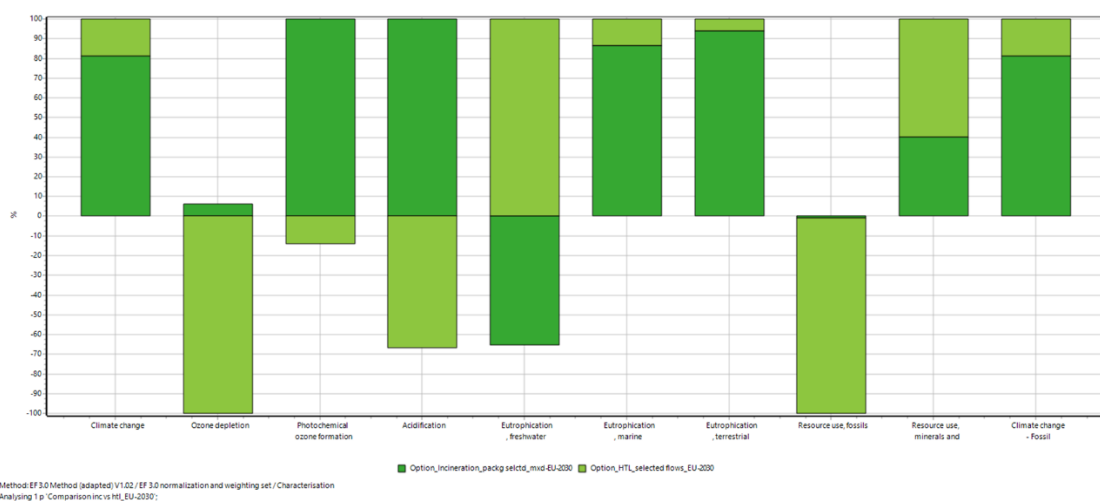


Figure 12 Life cycle impact of incineration and HTL for all plastic packaging waste that is not mechanically recycled in Europe, 2030

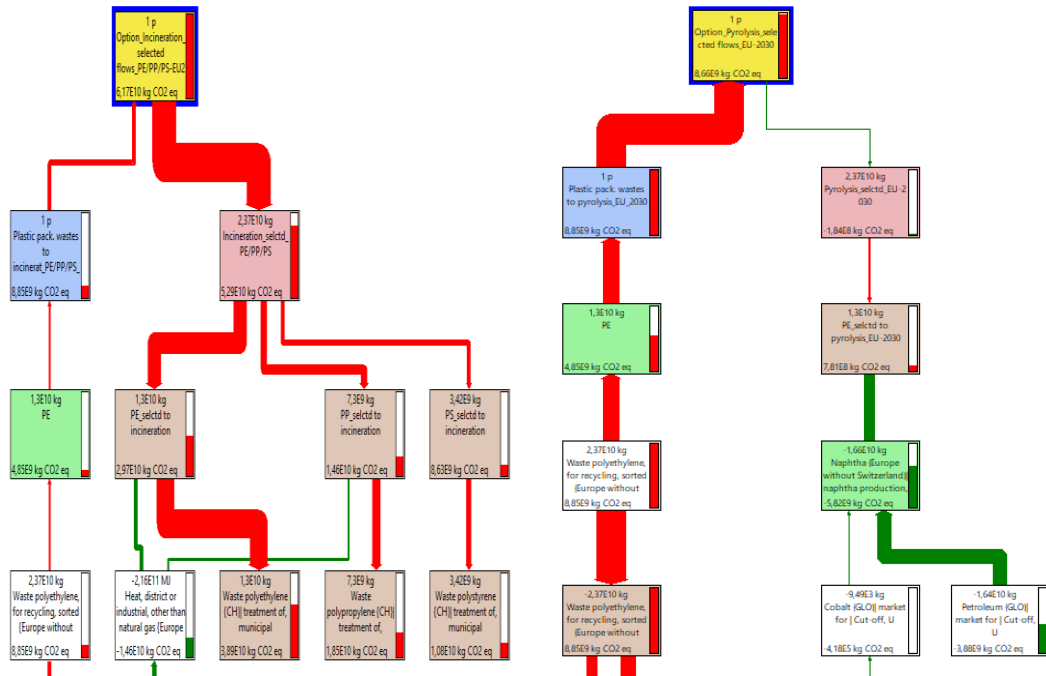


Figure 13 Climate change impact of incineration (left) and pyrolysis (right) of PE, PP and PS wastes not mechanically recycled in Europe, 2030

The climate impacts of incineration and pyrolysis of all polyolefins (PE and PP) and PS not mechanically recycled in Europe in 2030 are shown in Figure 13. Pyrolysis of these waste streams result in 8.66E9 kg CO_{2 eq} emissions compared to 6.17E19 kg CO_{2 eq} emissions for when these waste types are incinerated. Even though the avoided emissions due to incineration (-1.46E10 kg CO_{2 eq}) is much more than that from pyrolysis (-5.82E9 kg CO_{2 eq}), the process emissions from incineration more than offsets these benefits and this results in a higher net release of atmospheric emissions (climate impact) than pyrolysis.

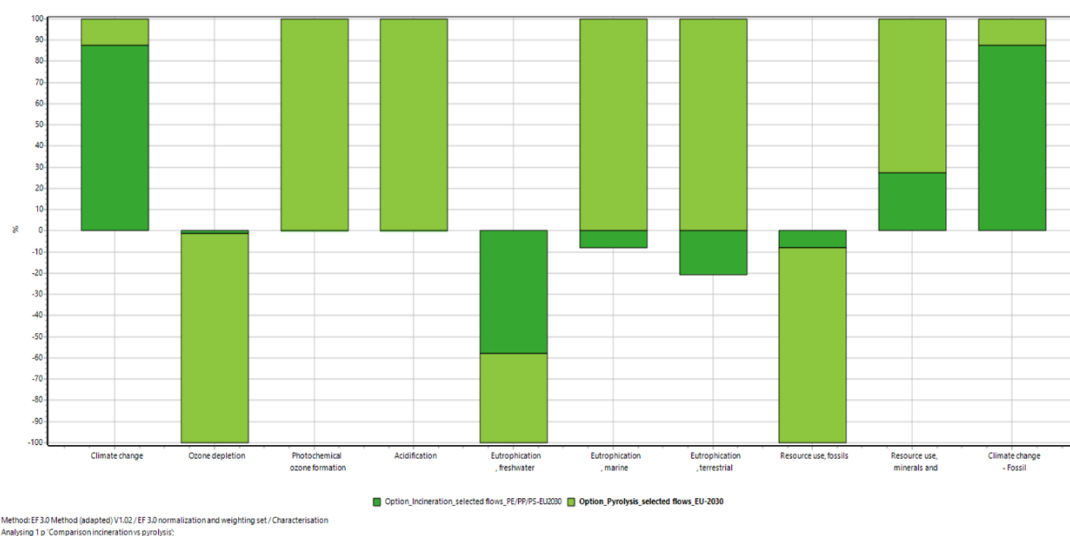


Figure 14 Life cycle impact of incineration and pyrolysis of polyolefins (PE and PP) and PS not mechanically recycled in Europe, 2030.

The results for the selected impact categories for the incineration and pyrolysis of all polyolefins (PE and PP) and PS not mechanically recycled in Europe in 2030 are presented in Figure 14. Pyrolysis performs better in the impacts categories of climate change, ozone depletion and fossil resource use while incineration performs better in the other categories. The trends observed here are similar to those reported in other studies^{60,61}, where incineration performed better in most of the selected impact categories.

Depolymerization (glycolysis) of all PET that is not recycled mechanically recycled in Europe, 2030

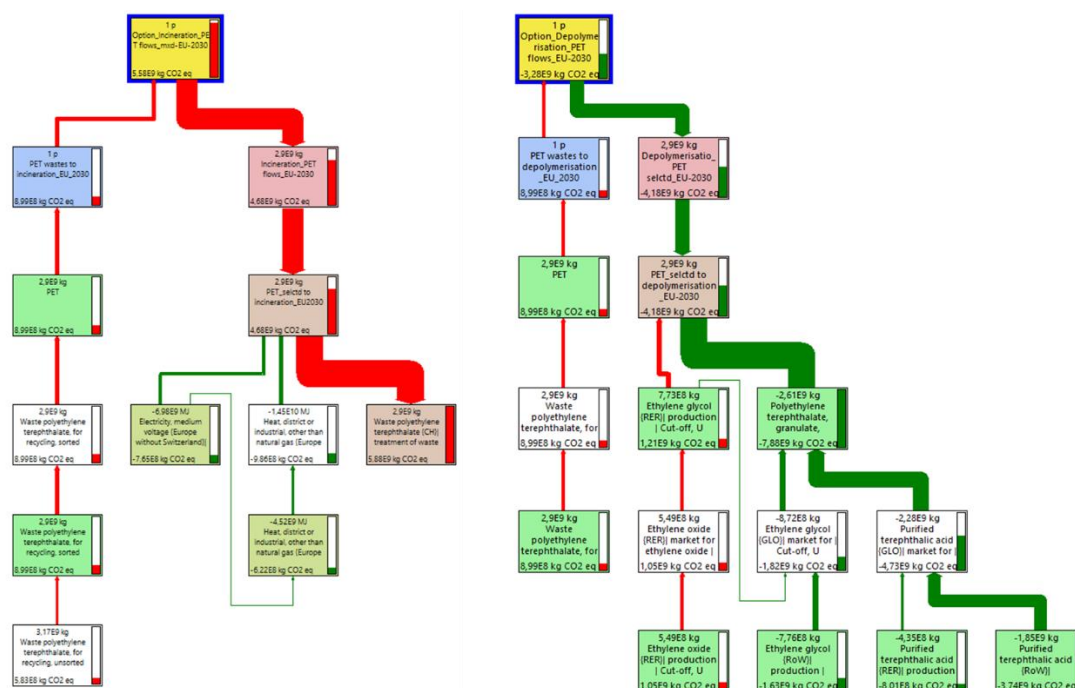


Figure 15 Climate change impact of incineration (left) and depolymerization/glycolysis (right) of all PET that is not recycled mechanically recycled in Europe

Figure 15 shows the climate impacts of incineration compared to depolymerization of all PET waste flows not mechanically in Europe by 2030. Depolymerisation gives net climate benefits (-3.28E9 kg CO₂ eq) while incineration results in net emissions (5.58E9 kg CO₂ eq) to the atmosphere. The energy and material input required for the depolymerisation result in significantly lower impacts compared to incineration. The depolymerisation process also seems much more efficient, giving larger benefits from the avoided virgin production of the substituted materials.

⁶⁰ Faraca G., Martinez-Sanchez V., Astrupa T. F. Environmental life cycle cost assessment: Recycling of hard plastic waste collected at Danish recycling centres. Resources, Conservation & Recycling 143 (2019) 299–309.

⁶¹ Jeswani, H., Krüger, C. M. Russ M. et al. Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. Science of the Total Environment 769 (2021) 144483.

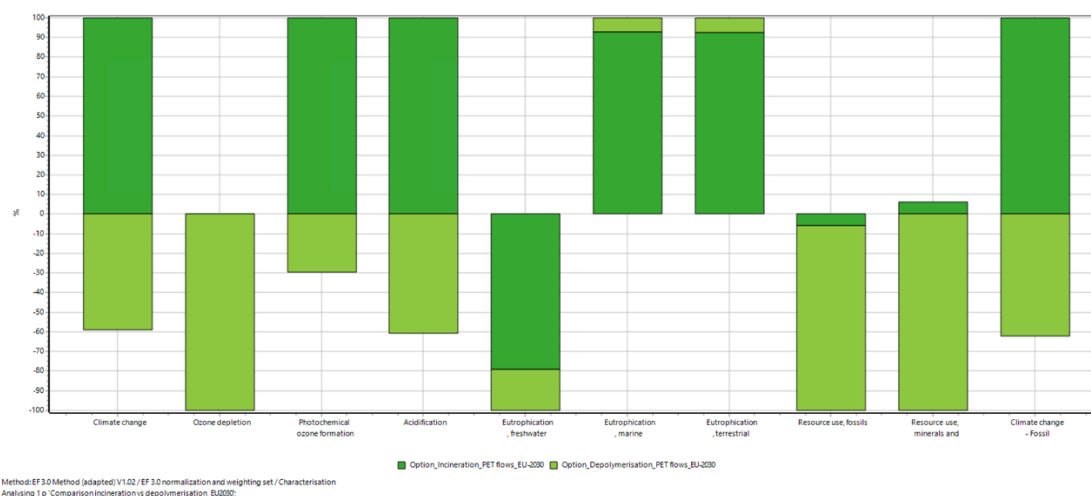


Figure 16 Life cycle impact of incineration (left) and depolymerization (glycolysis) of all PET that is not recycled mechanically recycled in Europe

The results for the selected impact categories for incineration compared to depolymerization presented in Figure 16 show that except for freshwater eutrophication, depolymerization performs better in all other categories. The depolymerisation process requires input of ethylene glycol and a metal oxide catalyst, which may have resulted in the higher freshwater eutrophication impact.

Gasification of all plastic waste not mechanically recycled by in Europe, 2050

The following figures show the potential climate impact of incineration compared to gasification of all plastic wastes that are not mechanically recycled in Norway (Figure 17) and Europe (Figure 18) by 2050. This is based on the assumption of a more sustainable future. Unlike the situation for Norway and Europe for 2030, where gasification gives net climate benefits (see Figure 5 and Figure 7), for 2050 gasification results in net release of atmospheric emissions due to the underlying assumptions. Here it's assumed that the electricity input for the gasification process is fully based on renewable sources and that the fuels for the transport of the sorted wastes to gasification plants is based on biofuels (thus modelled as CO₂ – neutral based on simplified assumptions). The sorting and pre-treatment processes are also assumed to be more efficient thanks to technical development, standardization measures and changes in design. The avoided emissions due to gasification by 2050 are from the substitution of biomass-based methanol production, compared to fossil based production for 2030.

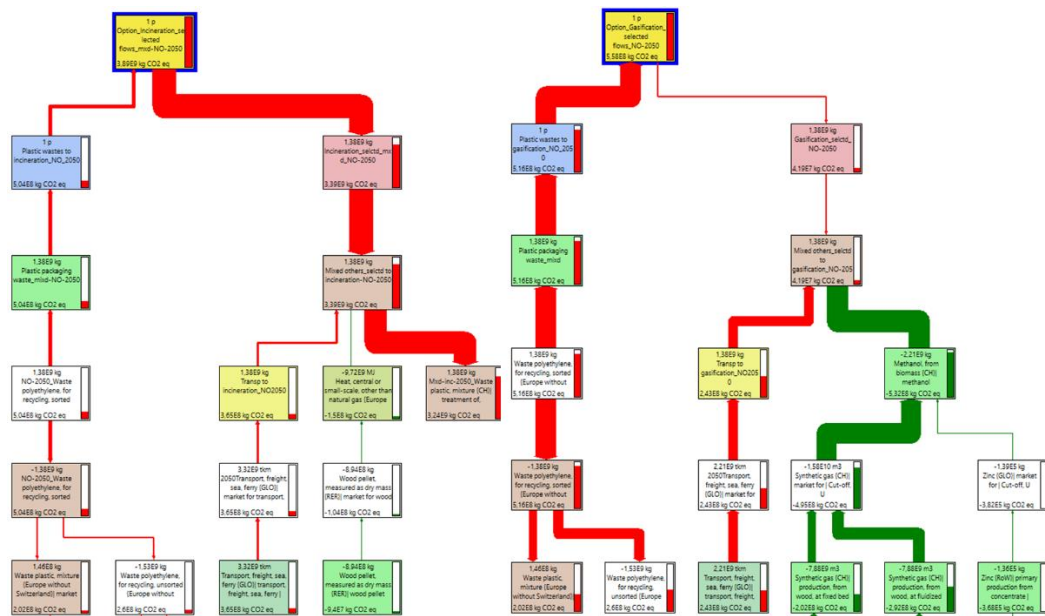


Figure 17 Climate change impact of incineration (left) and gasification (right) of all plastic wastes not mechanically recycled in Norway based on 2050 assumptions of a more sustainable future

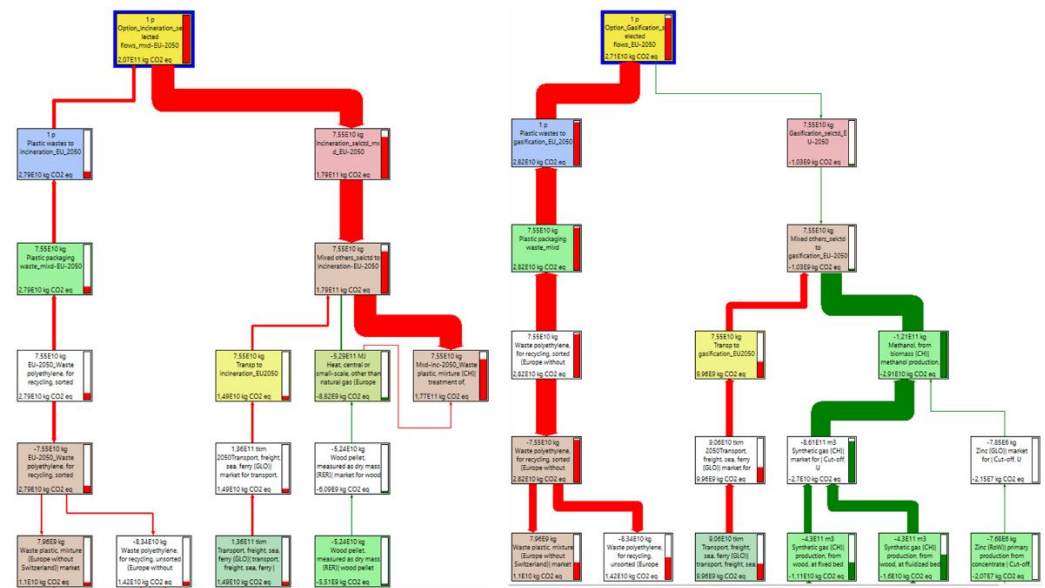


Figure 18 Climate change impact of incineration (left) and gasification (right) of all plastic wastes not mechanically recycled in Europe based on 2050 assumptions of a more sustainable future.

The results for the selected impact categories for incineration compared to gasification presented in Figure 19 for Norway and Figure 20 for Europe also reflect these results. However, the environmental performance of gasification remains superior to that of incineration in all respects. It should also be noted the positive impact of gasification on resource use, which can be a decisive criterion under the assumptions made.

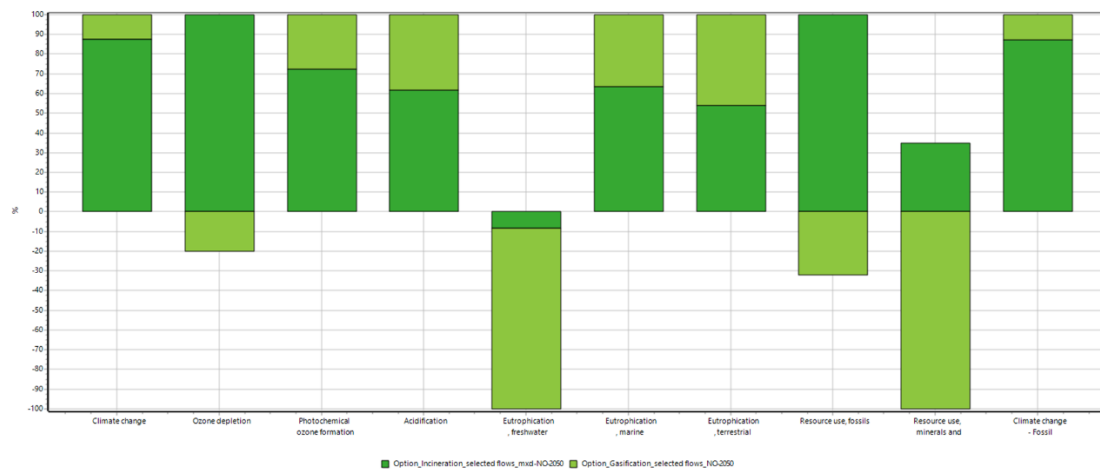


Figure 19 Life cycle impact of incineration and gasification for all plastic wastes not mechanically recycled in Norway, 2050

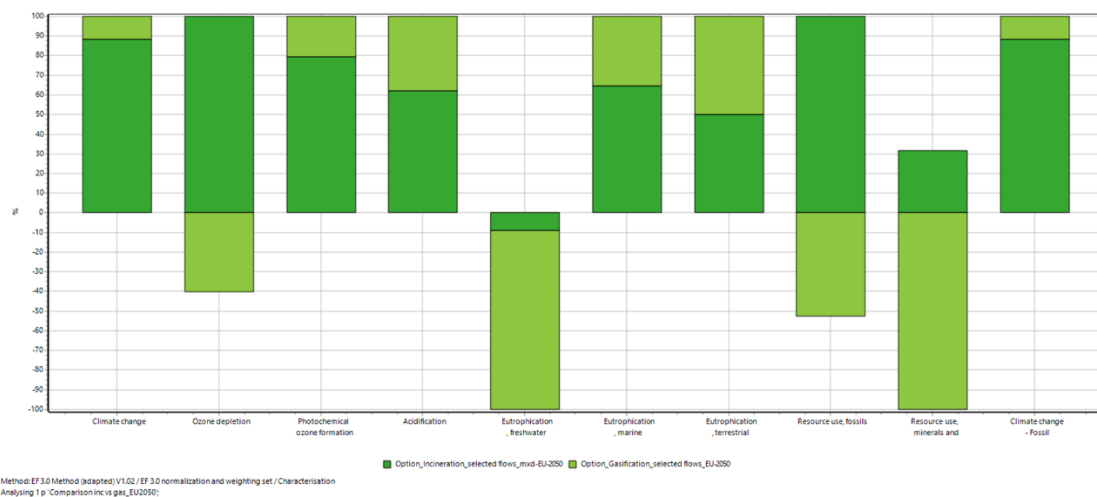


Figure 20 Life cycle impact of incineration and gasification for all plastic wastes not mechanically recycled in Europe, 2050

Interpretation of results

When analyzing the results obtained, it is important to remember that they were obtained under the severe constraints caused by, first and foremost, insufficient knowledge of the industrial operation of processes and structure/composition of waste material flows, but also constraints associated with the immaturity of the circular waste management system, including inadequate logistics, incomplete sorting, etc. Both the world of plastics and the world of waste management will have to undergo major changes in the near future in order to support circular use of resources, which will inevitably affect further development of recycling technologies. In addition, it can already be foreseen that the development of related technologies, such as CCS/CCU, may revolutionize our understanding of priorities. Just as the use of renewable energy has put an end to the perception of energy consumption as the only crucial parameter for the environmental friendliness of a process, so the utilization of carbon dioxide can change our understanding of CO₂ emissions as the central parameter for environmental impact.

At the same time, such a parameter as the use of resources will obviously not lose its importance and relevance. The global economy is currently consuming 70% more virgin

materials than the world can safely replenish: annual resource use was 89.8 billion tons in 2016 but exceeded 100 billion tons in 2019 and is estimated at 101.4 billion tons last year⁶². It is critical to limit the need to use virgin materials. Keeping materials in circulation by choosing the right recycling method is one of the main levers for such a limitation⁶³. Therefore, the authors suggest to keep in mind the critical importance of such a criterion as resource use when assessing the sustainability of future investments.

The assessments made in this study have in good faith taken into account both the features of the current system and its expected changes, such as (i) increased amounts of plastic waste, (ii) more complex polymer-based materials and products in waste streams, (iii) improvements in mechanical recycling, (iv) better and more efficient sorting due to standardization and improved design, and (v) increased use of renewable resources (green fuel/logistics and biobased plastics).

From the results obtained, we see that all chemical recycling options have advantages compared to incineration in terms of CO₂-equivalents per functional unit. Even though pyrolysis and HTL options result in net release of atmospheric emissions, they still outperform incineration by almost an order of magnitude. The same ratio is demonstrated in the analysis of gasification vs incineration in 2050.

At the same time, decarbonization does not mean simultaneous dephosphorization, or denitrogenation, or desulfurization. The same factors that lead to decarbonization can affect parameters such as acidification, eutrophication, and photochemical ozone production in different, sometimes opposite ways. This is important to consider when analyzing results that are not CO₂-related.

Conclusions

This study evaluated environmental potential of different chemical recycling methods to treat currently non-recyclable plastic waste in Norway and Europe, and analyzed the objective factors that currently prevent a correct assessment. The environmental potential for chemical recycling is assessed using LCA method against the incineration scenario. No comparison is made with mechanical recycling of plastics because only materials that cannot be mechanically recycled are considered as raw materials for chemical recycling. It is worth mentioning that some studies have concluded that for certain types of polymers, chemical recycling may surpass mechanical recycling, which is the case in, for example, study by Schwarz et al⁶⁴. on polyolefins. Although such a situation seems possible, this conclusion should be treated with caution in today's assessment environment, when mechanical recycling is not perfect, chemical recycling is not yet sufficiently developed, and the system is not adapted to maintain circular material flows in many of its parts, from design to logistics. Inaccuracies in estimation under these conditions can be significant. Therefore, bearing in mind that the existing hierarchy of processing methods can be challenged, such a conclusion should be additionally checked when new data become available, and the sensitivity of such a result to inaccuracies in various input data should also be investigated.

Based on the assessment made in this study it can be concluded that:

⁶² <https://www.recycling-magazine.com/2022/01/19/world-consumes-half-a-trillion-tonnes-of-virgin-materials-since-paris-agreement/>

⁶³ <https://www.eea.europa.eu/publications/reducing-loss-of-resources-from>

⁶⁴ Schwarz, A. E., Ligthart, T. N., Bizarro, D. G., De Wild, P., Vreugdenhil, B., & van Harmelen, T. (2021). Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Management*, 121, 331-342

1. Gasification of the estimated 637,500 tonnes/year of mixed plastic waste that is not mechanically recyclable in Norway by 2030 can save approximately 1.34E8 kg CO₂ equivalents, while incineration of this waste can result in 1.58 E9 kg CO₂ eq emissions. The corresponding effects for 34,850,000 tons/year of mixed plastic waste in Europe can be 7.31E9 kg CO₂ eq emissions savings from gasification compared to 8.66E10 kg CO₂ eq emissions to the atmosphere from incineration.
2. It is assumed that by 2030 the amount of plastic waste will reach 750,000 tons/year for Norway and 41,000,000 tons/year for Europe and the mechanical recycling rates will reach 15 %.
3. HTL of all plastic packaging waste that is not mechanically recycled in Norway by 2030 can result in about 3.81E8 kg CO₂ eq less net emissions to the atmosphere than incineration of these waste flows, and in Europe in about 2.80E10 kg CO₂ eq less net emissions than from incineration.
4. It is assumed that by 2030 the amount of plastic packaging waste will reach 300,000 tons/year for Norway and 25,800,000 tons/year for Europe, accompanying the growth of the market. The mechanical recycling rate for plastic packaging is assumed to reach 36%.
5. Pyrolysis of all polyolefins and PS that are not mechanically recycled in Europe in 2030 can result in 8.66E9 kg CO₂ eq emissions compared to 6.17E19 kg CO₂ eq emissions in case this waste is incinerated. This estimation is made for the amount of PE waste in Europe reaching 18,200,000 tons/year, PP waste 9,700,000 tons/year, and PS waste 3,420,000 tons/year by 2030. 5,200,000 tons PE and 2,400,000 tons PP are estimated to be mechanically recycled annually at that time with the recycling rate of plastic packaging doubled. Due to the lack of relevant data similar analysis could not be performed for Norway.
6. Depolymerization (glycolysis) of all PET in Europe that is not recycled mechanically by 2030 has a potential to bring net climate benefits of -3.28E9 kg CO₂ eq while incineration of this stream can result in net emissions of 5.58E9 kg CO₂ eq to the atmosphere.
7. It is assumed that by 2030 the amount of PET waste in Europe will reach 6,900,000 tons. The (mechanical) recycling rate for PET is expected to double and reach 58% by 2030. Due to the lack of relevant data similar analysis could not be performed for Norway.
8. Long-term prospects (by year 2050) of gasification of all plastic waste that is not recycled mechanically is analyzed with the amount of plastic waste estimated based on a conservative business-as-usual scenario. Such a scenario predicts that the amount of plastic waste will reach 1,728,000 tons in Norway and 94,400,000 tons in Europe. Mechanical recycling is projected to plateau at 14-22% by 2050.
9. Gasification of all plastic waste that is not recycled mechanically in Norway by 2050 can result in 5.58E8 kg CO₂ eq emissions compared to 3.89E9 kg CO₂ eq emissions from incineration. The corresponding numbers for Europe can be 2.71E10 kg CO₂ eq from gasification compared to 2.07E11 kg CO₂ eq emissions from incineration. It is expected that the development of CCS/CCU technologies may affect the result of this assessment, but it is currently not possible to give any reliable assessment of this impact, let alone quantify it.

Among the many uncertainties associated with underdevelopment, be it technology, logistics, sorting or other parameters, one of the significant uncertainties affecting the assessment is associated with insufficient information about existing waste streams. Obtaining more accurate information about the composition of these streams would be extremely useful both for studying options for their chemical recycling and for a better understanding of many other systemic aspects.