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Climate impact of pyrolysis of waste plastic packaging in comparison with reuse and mechanical recycling

Commissioned by Zero Waste Europe and the Rethink Plastic alliance

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1 Executive Summary

The present study compares seven scenarios for the future of plastic packaging in the European Union (EU) from a climate perspective, following the projected amounts of recycled plastics needed by 2030.

In the context of the revision of the *Packaging and Packaging Waste Directive (PPWD),* the European Commission (EC) commissioned Eunomia, a British consulting firm, to consider the possible introduction of recycled content targets for plastic packaging by 2030. Based on the estimated future recycling content targets in plastic packaging, Eunomia determined recyclate quantities that must come as outputs from chemical recycling or mechanical recycling. Chemical recycling, in this case, means thermo-chemical (i.e. pyrolysis) recycling.

Two scenarios were proposed for plastic recycled content targets: medium (30%) and ambitious (40%). In the medium and ambitious scenarios for the recycled content, they estimated the necessary recycling capacities and gave them as an output of material. In this context, Eunomia considered chemical recycling as the only solution for the production of recyclate for use in contact-sensitive packaging. However, there are also ways to achieve this through mechanical recycling.

With this study, we calculate the impact of Eunomia's proposed scenario regarding greenhouse gas (GHG) emissions and carbon loss and compare it to other possible scenarios. These other scenarios include two aspects: the reduction of the total amount of plastic packaging waste, and a shift from Eunomia's proposed scenario based on chemical recycling towards more mechanical recycling. **In this study, mechanical and chemical recycling technologies are combined in the best possible way to respect the Paris Agreement commitments to limit global warming to 1.5 degrees Celsius.** This means that in addition to non-recyclable plastics, sorting residues from mechanical recycling are also fed into chemical recycling. For this, different scenarios were developed:

- "Chemical recycling scenario" (numbers as proposed by Eunomia);
- "Reduction scenario" (reduction of the total volume of plastic packaging);
- "Mechanical recycling scenario" (shift to more mechanical recycling);
- "Mixed scenario" (reduction plus shift to more mechanical recycling).

To **reduce the amount of packaging**, various measures were identified:

- Reduction of unnecessary packaging;
- Reducing packaging through innovation;
- Development of systems for reuse of packaging.

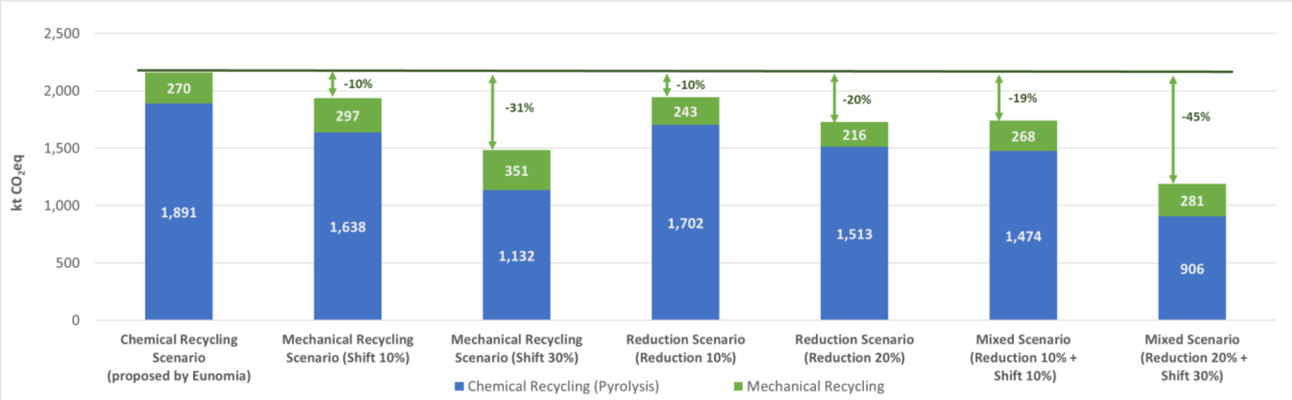
To achieve a **shift from** Eunomia's proposed scenario based on **chemical recycling towards more mechanical recycling**, the following measures were identified:

- Design for recycling;
- New collection systems;
- Innovation, e.g., layering systems.

For the GHG emissions no new life cycle assessments (LCA) were carried out, but data from representative and comparable LCAs are used. The data of the chemical recycling processes are taken as an average from two LCAs by Sphera commissioned by industry players with an interest in chemical recycling (The Consumer Goods Forum and BASF). The data must be viewed with caution, as the concept of chemical recycling on a commercial scale has not matured yet, and the data is based on a variety of assumptions which have not yet been proven, e. g. the one-to-one replaceability of virgin naphtha with pyrolysis oil. For mechanical recycling, this study used 2022 data from Oeko-Institut.

The present study shows that, in all scenarios considered, over 75% of the total GHG emissions are attributable to chemical recycling. This can be explained by the fact that **the emissions from mechanical recycling are lower than those from chemical recycling by a factor of 9**. Mechanical recycling causes a total of only 0.311 kg CO_2eq per kg of recyclate, while chemical recycling causes 2.91 kg CO_2eq per kg.

Another key finding is that shifting the output of chemical to mechanical recycling by 30%[1] would result in 31% of GHG emissions savings compared to the scenario based on data from Eunomia (henceforth known as "chemical recycling scenario"). Combining this shift with a reduction of 20% of packaging would result in a 45% reduction of GHG emissions compared to the "chemical recycling scenario".



GHG emission results for all seven scenarios - Based on the medium scenario from Eunomia (2020) (own representation)

In addition to the emissions of the recycling processes, the avoided production of new plastic is considered. The resulting GHG emissions savings are credited to the respective recycling processes. Given the current qualitative differences between recyclates from chemical recycling and mechanical recycling, a discount of 20% is applied to the credit of recyclates from mechanical recycling. **Despite this discount for the lower recyclate quality, the scenarios with a greater share of mechanical recycling lead to greater climate change mitigation than the scenarios with a lower share.** For example, **a shift of 30% from chemical to mechanical recycling leads to a 61% higher contribution to climate change mitigation** (illustrated by Figure 4 of this study)**.**

Another important result is the difference in carbon efficiency and the amount of carbon loss during the recycling processes. Taking the data from the aforementioned LCAs, **over half of the carbon is lost during the chemical recycling process (53%). For mechanical recycling, the loss amounts to 31%.** When calculating the overall carbon efficiency of the seven scenarios, the **"chemical recycling scenario" ends up with a total efficiency of 65%. By increasing the**

[1] Due to the higher share of mechanical recycling output in the medium chemical recycling scenario, this means that the output of chemical recycling is decreasing by 40%.

amounts of mechanical recycling by 30% (and simultaneously reducing the amount of chemical recycling), a total efficiency of 74% can be achieved.

The results of this study clearly show that **mechanical recycling should be preferred to chemical recycling wherever possible.** Measures such as design for (mechanical) recycling - i.e. monomaterial, simpler format, no hazardous chemicals - and other innovations must be facilitated to achieve this goal. In addition, it is important to reduce the overall amount of packaging to lower the GHG emissions in this sector **as it is not possible to achieve a zero-emission economy by recycling alone.**

If a chemical recycling industry is established in the coming years, this will affect the possibilities for treating plastic in the future. For as long as regulations do not introduce safeguards, the industry will use the cheapest and most easily material available (feedstock that can be actually recycled through mechanical recycling). Without adequate regulations, **efforts to strengthen mechanical recycling will be severely hampered**. Legal equality of chemical and mechanical recycling processes for packaging waste must therefore be prevented. **As such, the climate impact of different recycling technologies should be considered when setting targets for recycled content.**

2 Introduction

Following the *European Green Deal* and the new *Circular Economy Action Plan*, the European Commission (EC) is moving forward with proposals to shift towards a more circular economy. In many proposals, chemical recycling, especially pyrolysis,[2] is proposed as a general solution to problems with (non-recyclable) plastic waste. The debate focuses mainly on the question of how much chemical recycling is needed, and to which positive effect it can lead from an ecological and economic point of view.

Several studies have attempted to calculate the environmental impact of chemical recycling using life cycle assessments (LCAs), with many assumptions. The present study builds on these studies and uses their data. The recycled plastic streams needed are taken from the scenarios that Eunomia prepared on behalf of the EC for the forthcoming revision of the *Packaging and Packaging Waste Directive (PPWD)*. This study outlines the climate impacts that can be expected when the existing knowledge is combined; and how the negative climate impacts can be partially decreased.

As a result, this study clearly demonstrates that **efforts to reduce plastic consumption and improve mechanical recycling**, rather than focusing on pyrolysis as the main solution for plastic waste management, **are the appropriate way forward from a climate protection perspective**.

3 Scenarios and mass flows

This study aims to compare the climate impact of pyrolysis and mechanical recycling as feedstock for recycled content in the packaging sector[3] to achieve a circular economy for plastic. For this, different scenarios were developed:

- "Chemical recycling scenario" (numbers as proposed by Eunomia);
- "Mechanical recycling scenario" (shift to more mechanical recycling);
- "Reduction scenario" (reduction of the total volume of plastic packaging);
- "Mixed scenario" (reduction plus shift to more mechanical recycling).

The calculations of the different scenarios are based on the figures from Eunomia (2020) (Table 1). In the context of the forthcoming update of the *PPWD*, Eunomia is considering the possible introduction of targets for the recycled content of plastic packaging. Based on the estimated future recycled content targets in plastic packaging, recyclate quantities that must come as output from thermo-chemical thermal recycling (primarily pyrolysis) or physical recycling (mechanical and dissolution) were determined.[4] In the medium and ambitious scenarios for the recycled content, the necessary recycling capacities were estimated. . Eunomia assumed that all polyolefins for contact-sensitive materials would be recycled by thermo-chemical recycling; and polyolefins for all non-contact-sensitive materials by physical processes. Regarding the Eunomia figures, it should be noted

[2] ZWE categorises this technology as chemical recovery, but for this report, it is classified as chemical recycling.

[3] This paper focuses only on polyolefins (PO) since polystyrene (PS) has a very small share in packaging production (3.1% in Germany 2019, Conversio 2020) and polyethylene terephthalate (PET) is not suitable for pyrolysis.

[4] The waste input to the recycling plants was not stated in Eunomia (2022). As Eunomia does not publish any data or explicit assumptions for the calculation of output capacities, it was not possible to calculate them without adding uncertainties to the results. Since the present study is based on a comparative calculation (pyrolysis vs. comparative scenario), it is also irrelevant whether the calculation is based on the input or the output.

that the calculation of the required quantity of contact-sensitive packaging assumes that applications such as pharmaceuticals and cosmetics also require this quality. At least the cosmetics industry could use a material that is not allowed for food-contact application in some cases, e.g. for packaging of rinse-off products. For instance, the shower gel bottles of the company Frosch® are made of 100% recycled high-density polyethene (HDPE) from post-consumer recyclate (PCR) from the yellow bag (mixed food and non-food packaging waste) in Germany.[5] Taking this into account, the demand for pyrolysis output would be reduced without having to implement any of the measures mentioned later.

Table 1 Estimated Output Capacity Requirements for 2030[6]

	Chemical recycling (primarily pyrolysis) in kilo tonnes (kt)		Mechanical recycling plus dissolution (1) in kilo tonnes (kt)	
	medium	ambitious	medium	ambitious
Polyolefin recyclate	649	1,487	868	1,330

(1) Dissolution techniques are in all probability not yet available on an industrial scale in 2030, so it was assumed that the entire amount comes from mechanical recycling.

The figures in Table 1 from Eunomia form the basis of the scenarios.[7] All scenarios are calculated on the basis of both the "medium" and the "ambitious" scenarios.[8] In the "chemical recycling scenario", these figures are directly used for the calculations. Based on these figures and considerations from Eunomia, the comparison scenarios are developed.

The different scenarios diverge in the ratio between mechanical and chemical recycling and the total amount of packaging needed. The following sections describe the assumptions on which the shift to mechanical recycling is based, namely:

- Design for recycling;
- New collection systems;
- Innovation, e.g., layering systems.

Before improving the recyclability of plastic packaging, a reduction of the total packaging volume must be considered according to the European Waste Hierarchy. In the “reduction scenario”, calculations are carried out based on the assumption that the packaging volume is reduced in total by avoiding unnecessary packaging, reducing the volume and sizes, and by introducing reusable packaging systems.

When it comes to reusable packaging, its return and reuse are made possible by adequate logistics and promoted by suitable incentive systems. Reusable packaging systems are therefore embedded into a system/infrastructure and provided to the consumer as a service, under which the packaging’s reverse logistics (collection, washing, refill, and redistribution) are operated by the producer or a third party. It requires the existence of infrastructure, a suitable incentive to return the packaging (usually a deposit, but there are also systems in which the consumer pays a fine when the packaging is not returned), and a certain amount of minimum rotations, which should be at least between 10-15

[5] Werner & Mertz, *Press release “Weltneuheit im Kosmetikbereich!”*, 2019

[6] Eunomia, Targets for Plastic Recycled content in Packaging - PPWD Stakeholder Briefing, 2022

[7] The original table is found in the annexe - table 6.

[8] The results for the medium scenario are presented in the paper. The results for the ambitious scenario can be found in the annex.

cycles.[9] Some examples include reusable PET bottles as in the German deposit system, deposit systems for cosmetic products (e.g., CoZie) or food (Loop).

An example of the successful elimination of unnecessary packaging can be found in France with the introduction of a government ban on single-use plastic packaging for perishable products in January 2022.[10] Following the ban, it is estimated that one billion pieces of single-use plastics should be saved annually. Likewise, at Tesco (in the UK), multipacks are no longer packed in plastic film and the discount is automatically given at the checkout for loose cans. This simple software programming eliminated an estimated 350 tons of plastic film.[11]

Another way to support the prevention of packaging waste is to encourage refill on the go, with the customer bringing his container to the store and refilling there. Examples of this method include milk vending machines with fresh milk (The Milk Station Company - UK); refilling stations for dry foods like lentils, noodles, oats, etc. (e.g., MIWA); and refilling stations for detergents (e.g., NatureLoves).

There are no exact studies on how much reduction is possible through the various measures. Some studies focus on certain types of packaging and their reduction, but there are no publications on the reduction of the entire packaging volume. Therefore, the target reduction of the European Plastics Pact of 10% was used as one approach, and varied upwards in a second scenario for a more ambitious (20% reduction) approach. This results in two "reduction scenarios".

Since mechanical recycling is not a viable option for mixed plastics, pyrolysis is proposed as the solution to cope with this waste stream while still achieving high recycling rates. Another possible solution is to not simply accept the current waste properties as a given, but to consider the possibility of improving the recyclability of the packaging through design for recycling so that it is suitable for mechanical recycling. For example, a change in the complexity of packaging materials - going from multi-layer to single-layer films, fewer additives, or from dark to light packaging - leads to a change in the target fraction. This means that the packaging is no longer sorted into the mixed plastics fraction but the polyethene (PE) or polypropylene (PP) fraction, and can now be recycled into high-quality recyclate - resulting in a shift in volume away from pyrolysis toward mechanical recycling.

Pyrolysis is not the only way to meet the future EU targets for the recycled content of plastic packaging for contact-sensitive packaging. Mechanical recycling can also do it in a way that meet contact-sensitive requirements. However, mechanical recycling can not always provide this specific quality. Further development and innovation regarding sorting systems, mechanical recycling technology, and packaging design are needed to step mechanical recycling up. One example of this is layering systems. When looking at contact-sensitive packaging, it is usually considered that only the contact layer to the product needs to be of suitable quality and not the entire packaging to meet the legislation requirements. This means that the part of the packaging that is not in direct contact with the product could come from recyclate from mechanical recycling. This layering system could reduce the need for contact-sensitive material, thus decreasing the amount of required pyrolysis recyclate accordingly. The recyclability of this packaging with a layering system still has to, and can,

[9] Zero Waste Europe, *Packaging Reuse vs. Packaging Prevention - Understanding which policy measures best apply*, 2022

[10] JORF, *Décret n° 2021-1318 relatif à l'obligation de présentation à la vente des fruits et légumes frais non transformés sans conditionnement composé pour tout ou partie de matière plastique*, 2021

[11] Ellen MacArthur Foundation, *Eliminating unnecessary plastic packaging: Tesco*, 2021

be provided. A first example of such packaging is given by Trioworld[12] which currently uses 30% PCR in the second layer of their PE/PP packaging film.

Furthermore, the reason why recyclate from mechanical recycling cannot be used for food-contact packaging is not necessarily its lower processing quality[13], but rather stems from safety regulations.[14] Due to contamination risks (e.g. from non-food packaging containing harmful residues), it is currently forbidden to produce recyclate for food grade packaging from mixed input streams (food and non-food packaging). Separately recycling food packaging would minimise risks related to contamination, and the resulting recyclate could be reused in food packaging. For example, Biffa can use recycled HDPE milk bottles to make trays for fruit and vegetables with 70% recycled content. To recycle food packaging into food-grade material, an appropriate collection infrastructure is needed. That means expanding existing collection systems or setting up new ones would be necessary and can lead to higher recycling rates or better quality recyclates. Deposit return systems (DRS), such as those already in place in Germany for PET bottles, under which bottles are kept in a closed-loop system, could be extended to other packaging types and materials (e.g., HDPE bottles). Various approaches for non-food packaging show that it is possible to introduce a new collection system in addition to existing systems: there are already private-sector approaches and companies that offer new collection or deposit systems for shampoo and shower gel bottles, e.g., Circleback or Digi-Cycle.

Precise quantification of this shift away from pyrolysis toward mechanical recycling is not possible due to a lack of data. Therefore, two "mechanical recycling scenarios" were calculated: a shift from pyrolysis to mechanical recycling of 10%, and another of 30%. Finally, the reduction approaches were combined with the approaches for shifting toward mechanical recycling. Here, two "mixed scenarios" were calculated: a conservative one (10% reduction and 10% shift) and an ambitious one (20% reduction and 30% shift).

Figure 1 shows the resulting outputs from chemical (blue) and mechanical (green) recycling as well as the total output of recyclate (grey), based on the medium scenario from Eunomia (2020). The results for the ambitious scenario are in the annexe (Figure 5).[15]

[12] Trioworld, *Press release "Trioworld launches recycled food packaging with Lidl Sweden"*, 2022

[13] Lower processing quality means: lower viscosity of the recyclate due to broken polymer chains (e. g. no films can be thermoformed) or braking points in the product due to contamination by other polymers (e. g. films can brake during thermoforming).

[14] EFSA Journal, EFSA Panel on Food Contact Materials, Flavourings and Processing Aids: Scientific Opinion on the safety assessment of the processes 'Biffa Polymers' and 'CLRrHDPE' used to recycle high-density polyethylene bottles for use as food contact material, 2015

[15] In the ambitious scenario, the total output is about 85% higher than in the medium scenario (2.817 kt). The ratio between the output from chemical recycling and mechanical recycling is reversed. In the medium scenario, 43% of the recyclate comes from pyrolysis, 57% from mechanical recycling. In the ambitious scenario, 53% comes from pyrolysis and 47% from mechanical recycling. This is because Eunomia assumes an increase in recycling content targets of 40% for contact-sensitive (output from pyrolysis) but only 28% for non-contact-sensitive recyclate (output from mechanical recycling) for the ambitious scenario.

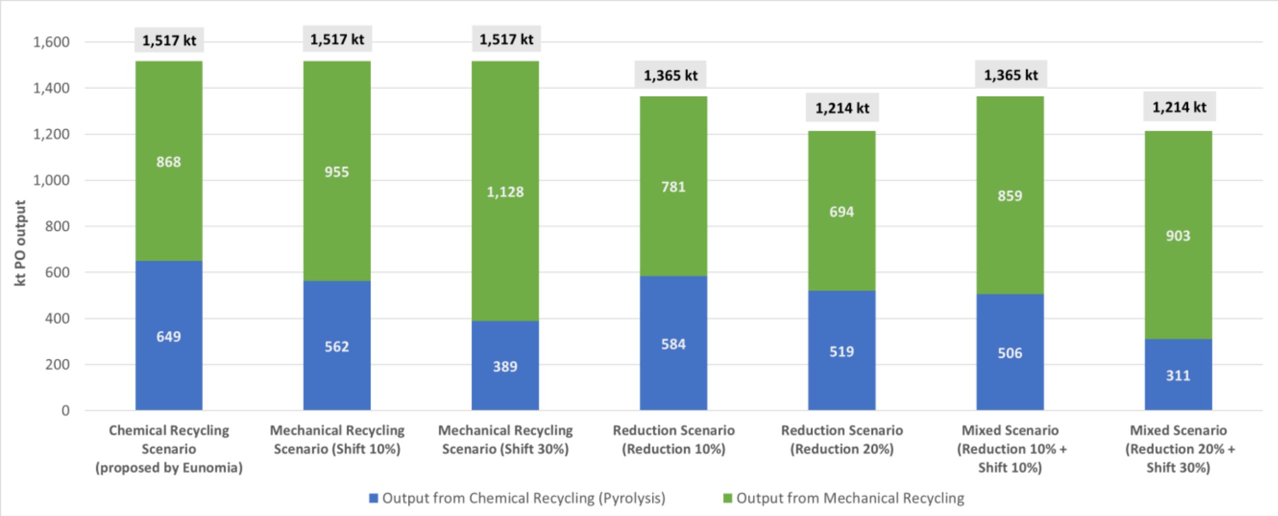


Figure 1 **Output quantities from chemical recycling (pyrolysis) and mechanical recycling for the different scenarios – Based on the medium scenario from Eunomia (2020) (own representation)**

4 Scope and assumed process scheme

Figure 2 shows the basic scheme on which the different scenarios are based. The goal is to calculate the amount of CO_2eq resulting from producing recycled plastic as feedstock for new packaging materials. Following the scenario by Eunomia, a certain amount of recyclate from mechanical and chemical recycling has to be produced (Figure 1).

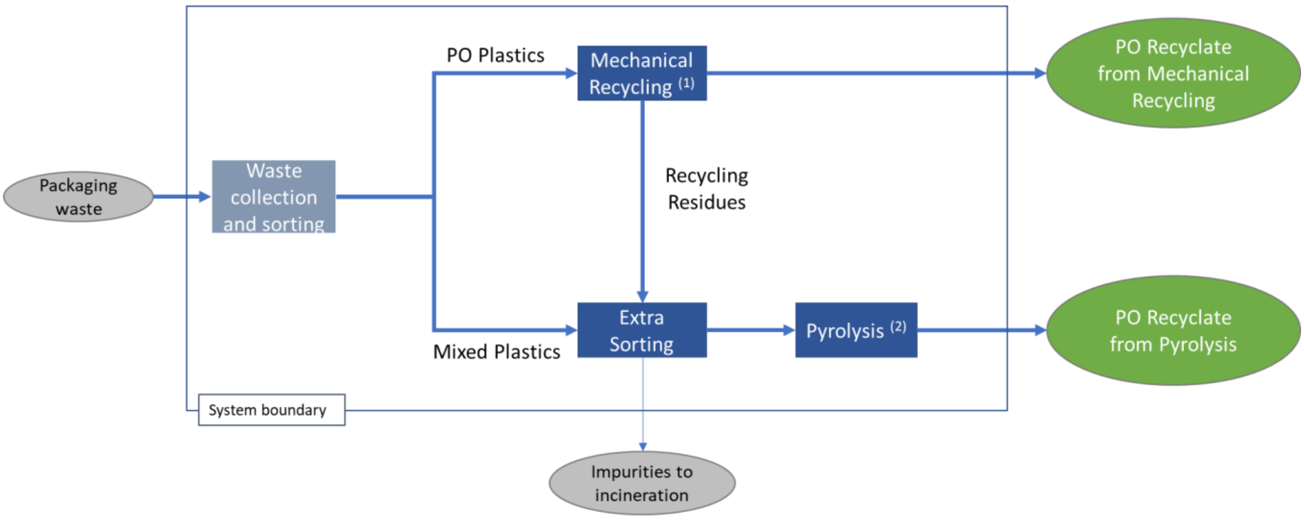


Figure 2 **Overview of the flows in the scenarios (own representation) (1) Recycling includes: Washing, further sorting, regranulation. (2) Pyrolysis includes: Pyrolysis, purification of pyrolysis oil, cracking and polymerisation.**

Packaging waste is taken to a sorting plant where polyolefinic plastics and mixed plastics are sorted out as two different fractions, one suited for mechanical recycling and one which is not. The fraction going into the mechanical recycling consists of polyolefins (PO), light-coloured mono-PE, or PP-packaging (films and hard plastics). It can be mechanically processed into recyclate and replaces primary plastic in various products. In the preliminary fraction for pyrolysis, called the mixed plastics fraction, the following plastic packaging is found:

- Plastic packaging, that is not positively sorted out (i.e., not part of a sorting fraction, e.g., biodegradable plastic, non-bottle PET);
- Coloured with carbon black (e.g., black shower gel bottles);
- Multilayer films (e.g., chip bags);
- PE/PP films smaller than A4 paper.

The mixed plastic fraction is not well suited for mechanical recycling. Most of this fraction is currently used for energy recovery and could be chemically recycled (by pyrolysis) instead. Before going into pyrolysis, the fraction is sent to an extra sorting step where plastics that are not suitable for pyrolysis (e.g. PET) are sorted out.

In the mechanical recycling of the PO fraction, there are so-called recycling residues. These not only consist of residues from recycling (e.g. paper labels) but also contain other impurities from the PO fraction (e.g. incorrectly sorted plastics). Currently, these are used for energy recovery, but in the future, they should also be chemically recycled. Hence, in this scenario, the recycling residues also go into an extra sorting step (in this case, simplified, into the same step as the mixed plastics). The sorted-out plastics that do not fit for pyrolysis (e.g. PET, PVC, PA) are treated in another way,[16] while the remaining fraction from this extra sorting then goes into the pyrolysis process. First, the plastics go into pyrolysis where they are converted into pyrolysis oil. This oil has to be processed and cleaned before it can be fed to the cracker to produce the base chemicals that fit for polymerisation, like ethylene. After further purification, it is followed by polymerisation to polymers PP and PE.

The analysis not only provides the greenhouse gas emissions for the combined processes but also includes a calculation of the carbon efficiency of the different scenarios. The carbon efficiency shows how much carbon is lost in the various scenarios, i.e. cannot be used again for new plastic. The temporal scope of the calculations is the year 2030, and the geographical scope is Europe.

5 Greenhouse gas (GHG) emissions

5.1 Data for chemical recycling (pyrolysis)

Data for GHG emissions for pyrolysis is taken from literature, no own LCA study was carried out. For this purpose, current LCA studies on the topic of pyrolysis of plastic packaging waste were collected and evaluated according to their use as a basis for calculating the pyrolysis scenario.

[16] In this study, this treatment is considered as incineration in a waste incineration plant.

A total of nine LCA studies[17,18,19,20,21,22,23,24,25] from the last three years were reviewed. The following points were considered important criteria for the selection of the studies:

- Results must be presented as a number, not just as a graph;
- Results must be presented in a transparent and differentiated way (results that included processes not considered could not be used);
- Output must be at least one type of polyolefin (not naphtha or olefins as in some of the studies reviewed);
- Input should be mixed plastic waste not suitable for mechanical recycling since this is the plastic waste that the chemical recyclers are currently targeting.

Table 2 shows two LCA studies that meet all criteria - both were carried out by Sphera. In part, the same assumptions are made (especially for the collection and sorting of waste); but the results are very different. Based on the studies, the origin of this significant difference is unclear. The mean value of the two studies (2.91 kg CO_2eq/kg output) was therefore used as the calculation value for the present work.

Table 2 Overview of eligible LCA studies

Source	Financed/Commissioned	Geographic scope	Input	Output	Results *in kg CO_2eq/kg recyclate output*
Sphera 2022	The Consumer Goods Forum (1)	Europe	Mixed plastic waste	PE/PP mix	2.48
Sphera 2020	BASF	Germany	Mixed plastic waste	LDPE (2)	3.35

(1) 400 retailers, manufacturers, service providers, and other stakeholders across 70 countries. https://www.theconsumergoodsforum.com

(2) in scenario 2 (the other two scenarios in this study cannot be used because output is either naphtha and not a polymer (scenario 1) or output quantity is not specified (scenario 3))

When interpreting the results of these LCAs, some points need to be considered:

[17] Vollmer et al, *Die nächste Generation des Recyclings – neues Leben für Kunststoffmüll*, 2020

[18] Sphera Solutions GmbH, Life Cycle Assessment of Chemical Recycling for Food Grade Film, 2022

[19] Volk et al, Techno-economic assessment and comparison of different plastic recycling pathways - A German case study, 2021

[20] Schwarz et al, Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach, 2020

[21] Keller et al, Life cycle assessment of global warming potential, resource depletion and acidification potential of fossil, renewable and secondary feedstock for olefin production in Germany, 2020

[22] Sphera Solutions GmbH, Evaluation of pyrolysis with LCA - 3 case studies, 2020

[23] Broeren et al, *Exploration of chemical recycling, What are - and will be - the opportunities for climate policy?*, 2019

[24] Meys et al, *Towards a circular economy for plastic packaging wastes – the environmental potential of chemical recycling*, 2020

[25] Muscat et al, *The battle for biomass: A systematic review of food-feed-fuel competition*, 2020

- Data on the environmental impacts[26] of chemical recycling should be viewed with caution, as the concept of chemical recycling on a commercial scale is not yet mature. There are currently no chemical recycling plastic-to-plastic plants in industrial operation.
- In the BASF LCA, data for the pyrolysis technology of a commercial manufacturer from 2018 was used, without further indication of who this manufacturer is. The purification steps of pyrolysis outputs were based on primary lab-scale data. The data for the cracker comes from BASF itself and is not published due to confidentiality - even the reviewers of that study did not have access to it. In the second LCA,[27] data for the pyrolysis process derived from three pyrolysis companies in Europe. Due to confidentiality, no further details were provided here either. The cracking process was taken from the LCA database GaBi, which was actually developed for cracking virgin naphtha. Because of these undisclosed data instances, there is no possibility to reproduce the studies to verify their findings, which undermines their credibility.
- It has not yet been proven that pyrolysis oil behaves exactly like naphtha.
- The industry claims (e.g. in BASF's LCA)[28] that the incineration of pyrolysis gas produced during the pyrolysis of plastic waste can cover almost the entire energy demand of the process. There is a clear conflict of objectives here between using the pyrolysis products (pyrolysis oil) to manufacture new products and using by-products (pyrolysis gas and coke) to provide energy for the pyrolysis process itself. If the goal is to maximize the yield, then less and less pyrolysis gas will be left as a by-product to run the process, which would lead to a further need for external energy supply. If the industry manages to increase the pyrolysis oil yield in the future, it will have to supply more and more external energy. The claim of a self-sustaining process will then no longer be valid.

5.2 Data for mechanical recycling

Data of GHG emissions for mechanical recycling is taken from Oeko-Institut 2022 (Table 3). GHG emissions for the use of electricity, heat, diesel, chemicals, tap water, and wastewater treatment for mechanical recycling were considered. The European electricity mix and heat from natural gas in Europe were used to calculate the GHG emissions. According to the geographical scope of Oeko-Institut (2022), the results represent the state of the art of mechanical recycling in Germany. Considering the reference year of the present work (2030) and the fact that plastic recycling in Germany is relatively advanced, the results can be transferred to the EU level. According to Oeko-Institut (2022), about 50% of the PO fraction that goes into mechanical recycling consists of PE and PP foils, which are recycled into regranulate. The other 50% is hard PE and PP packaging. On average, the PO yield in mechanical recycling is 68.7%. This means that from, one ton of PO that goes to mechanical recycling, 687 kilograms of PO are recovered as recyclate. The remaining 31.3% are recycling residues that go to pyrolysis (see Figure 2). In addition to the state-of-the-art, a more conservative yield of 63.5%[29] was also calculated. As per Table 3, the change in yield has only a minor influence on the results of the GHG emissions of mechanical recycling.

[26] Environmental impacts are not limited to the emission of CO_2 or its effects on climate change, but also include other emissions that can lead to further environmental impacts such as eutrophication, acidification and ozone formation.
[27] Sphera Solutions GmbH, Life Cycle Assessment of Chemical Recycling for Food Grade Film, 2022
[28] Sphera Solutions GmbH, Evaluation of pyrolysis with LCA - 3 case studies, 2020
[29] Oeko-Institut e.V., *Life cycle assessment of the services of the dual systems in the field of packaging recycling*, 2022

Table 3 **Yields and GHG emissions for mechanical recycling of polyolefins**

Yield	GHG emissions *in kg CO2eq/kg recyclate output (1)*
68.7%	0.311
63.5%	0.337

(1) without considering the further utilization of the recycling residues

The 0.311 kg CO_2eq per kg recyclate output for mechanical recycling is nearly an order of magnitude lower than the 2.91 kg CO_2eq per kg recyclate output for chemical recycling. In the proposed scenario, however, pyrolysis also takes care of the residues from mechanical recycling. The emissions from their treatment are neglected here. Nevertheless, these numbers clearly demonstrate that the more mechanical recycling can take place due to the steps described in chapter 3, the bigger the overall benefit considering the GHG emissions.

5.3 Results

Figure 3 shows the results regarding GHG emissions for all scenarios based on Eunomia's medium scenario.[30] Although the share of mechanical recycling is higher (57% compared to 43%), GHG emissions are mainly caused by pyrolysis in this case. Increasing the amount of output by mechanical recycling by 30% and decreasing the output from pyrolysis by the same amount[31] (Mechanical Recycling Scenario Shift 30%) results in a GHG reduction of 31%. Reducing plastic consumption overall by 20% (Reduction Scenario 20%) also reduces GHG emissions by 20%. Combining these two scenarios (Mixed Scenario) results in a GHG reduction of 45%. These results show that a combination of efforts to reduce plastic consumption and improve the recyclability of packaging leads to the highest possible reduction of GHG emissions .

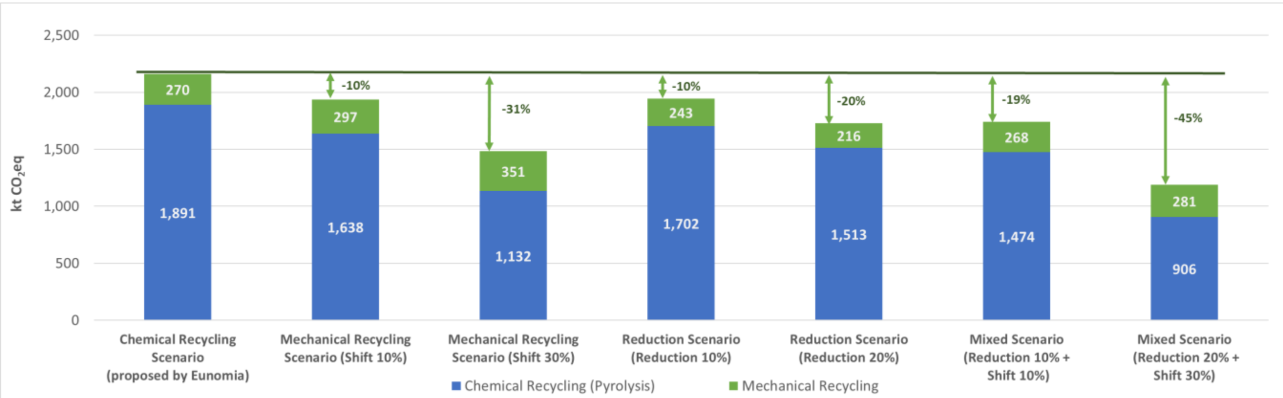


Figure 3 **GHG-Emission results - Based on the medium scenario from Eunomia (2020) (own representation)**

[30] The results based on Eunomia's ambitious scenario are shown in the annex (Figure 5). They show the same picture as those based on the medium scenario. The reduction contributions are slightly lower than in the medium scenario.

[31] This means that the output of pyrolysis is decreasing by 40.1%, as the mechanical recycling output used in the calculation of the 30% shift is larger in the medium scenario by Eunomia.

To check the influence of the different assumptions and uncertainties on the result, sensitivities[32] needed to be calculated. In the **first sensitivity analysis**, the yield of mechanical recycling was reduced from 68.7% to 63.5% (cf. Table 3 above). In both the medium-based and the ambitious-based scenarios, this only resulted in a change of 1-3% in the overall result.

In the **second sensitivity analysis**, the credit for replacing primary plastic was taken into account. The recyclate generated through chemical and mechanical recycling is used in products and replaces primary plastics (from fossil raw materials) - thus avoiding the producing of new primary plastic. The resulting GHG emissions saving is credited to the respective recycling process. Considering the current qualitative differences between recyclate from pyrolysis and mechanical recycling, a discount of 20% was added to the credit for recyclate from mechanical recycling. The explanation of the calculation of the credit and the net result can be found in the Annex. Figure 4 shows the net results for the sensitivity.

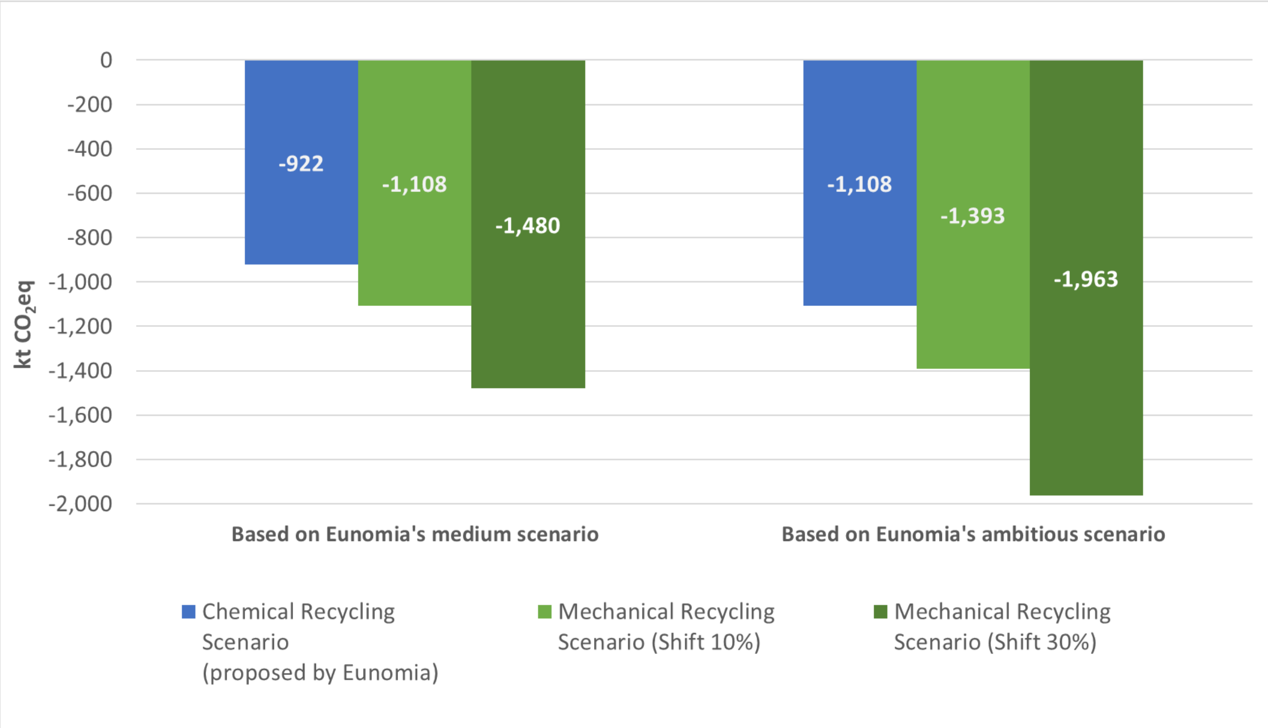


Figure 4 **GHG results second sensitivity (incl. credits)**

Despite the discount for the lower recyclate quality, the "mechanical recycling scenario" leads to greater climate change mitigation than the "chemical recycling scenario". With a shift of 10%, the "mechanical recycling scenario" contributes 20% (or 26% for ambitious) more to climate change mitigation than the "chemical recycling scenario". When a shift of 30% from mechanical to chemical recycling occurs, this value goes up to 61% (or 77% for ambitious). The results of this sensitivity analysis show that, despite the (still existing) differences in the quality of recyclates, mechanical recycling should be prioritised from a climate perspective. The pyrolysis of plastic packaging should only serve as the last step in the prioritisation in order to avoid the total loss of carbon from the cycle due to incineration and landfill.

[32] Element from LCAs to take into consideration external factor affecting techologies yield.

6 Carbon efficiency

To calculate the carbon efficiency of a scenario, the input is required in addition to the already known output. This was calculated based on the efficiencies given in Sphera 2020 and Sphera 2022 (for chemical recycling) and Oeko-Institut 2022 (for mechanical recycling). Table 4 shows the yields of the different stages of chemical and mechanical recycling. Most losses in chemical recycling occur during pyrolysis of waste and cracking of the pyrolysis oil. The overall yield of chemical recycling is the product of the individual steps. The average value from Sphera 2020 and 2022 was again used as the calculation value (efficiency chemical recycling: 0.470). This means that **pyrolysis is assumed to have a loss of 53% of the material under ideal conditions**, as the values come directly from the industry. Mechanical recycling leads to carbon losses through the recycling residues (efficiency mechanical recycling: 0.687). As such, **mechanical recycling is assumed to have a loss of 31% of the material**.

Table 4 Yields of the individual steps in chemical recycling (pyrolysis) and mechanical recycling

	Sphera 2020	Sphera 2022	Oeko 2022
Extra sorting	0,900	0,900	
Pyrolysis	0,756	0,703	
Purification	0,939	0,980	
Cracking	0,731	0,797	
Polymerisation	0,971	0,980	
Overall Pyrolysis	**0,456**	**0,484**	
Mechanical Recycling			0,687
Extra sorting of recycling residues			0,800 (1)

(1) assumption

Here it was assumed for simplicity that the recycling residues from mechanical recycling have the same carbon content as PO. In reality, this is not the case. The carbon content is usually lower because the recycled residues also contain e.g. paper labels and other materials with lower carbon content. This should result in a lower carbon loss for mechanical recycling. To keep it simple, the given value is nevertheless used.
The overall efficiency of the different scenarios is calculated according to formula 1.

$$Efficiency = \frac{Output}{Input} = \frac{C+D}{A+(B+E)} \qquad (1)$$

C is the output of mechanical recycling and D the output of pyrolysis. For the input, A represents the input of mechanical recycling, while B and E resemble the input into the pyrolysis (B: mixed plastics and others; E: sorted recycling residues). If more residues come from mechanical recycling, the input from other sources like mixed plastic waste can be smaller. For an illustration of the variables, see Figure 7 in the annexe.

A single reduction of plastic packaging does not change carbon efficiency. Therefore, it is only calculated for the scenarios "chemical recycling" and "mechanical recycling". The results are given in Table 5. The results show that shifting plastic packaging waste away from chemical recycling towards mechanical recycling increases carbon efficiency. This means that **the more waste is treated through mechanical recycling, the less carbon is lost and, correspondingly, less**

primary carbon has to be used to compensate. For the scenarios based on Eunomia’s medium scenario, an increase of 5% in the amount of waste treated in mechanical recycling leads to a 2% improvement in carbon efficiency. An increase of 30% in mechanical recycling leads to a 13% improvement in carbon efficiency. As described above, in Eunomia's ambitious scenario 53% of the recyclate comes from pyrolysis, while in the medium scenario that amounts to 43%. For this reason, the carbon efficiency for the four calculated scenarios is lower when based on the ambitious figures.

Table 5 Carbon efficiency results

		“Chemical Recycling scenario”	***“Mechanical Recycling Scenario (Shift 10%)”***	***“Mechanical Recycling Scenario (Shift 30%)”***
Eunomia’s medium scenario	Sum Output (kt)	1.517	1.517	1.517
	Sum Input (kt)	2.327	2.237	2.058
	Total Efficiency	**65%**	**68%**	**74%**
Eunomia’s ambitious scenario	Sum Output (kt)	2,817	2,817	2,817
	Sum Input (kt)	5,098	5,008	4,829
	Total Efficiency	**55%**	**56%**	**58%**

7 Discussion

The chemical recycling scenario causes between 2.4 and 5.0 Mt CO_2eq per year for the medium and ambitious scenarios, respectively. To put the GHG emissions into perspective, in 2020 the emissions of Malta were of 1.6 Mt and the ones of Luxembourg amounted to 8.0 Mt CO_2eq .[33] As discussed earlier, these emissions are mainly caused by chemical recycling (over 80% in the medium chemical recycling scenario). Although recycling and the use of the resulting plastic reduce the emissions compared to new plastic, these emissions further cause the overall carbon budget to shrink and have to be reduced to zero as soon as possible. This is, however, very difficult to achieve. The emissions for pyrolysis come mainly from the burning of the pyrolysis gas for the heating of the pyrolysis oven. Although this is a way of disposing of the mixture of different gases resulting from the pyrolysis process itself, it is not reasonable course of action in a carbon-neutral society. The oven can be heated by electricity; however, the problem of disposing of the pyrolysis gas remains. While it is relatively easy to reduce the emissions from the mechanical recycling process itself to 0 by replacing the overall energy consumption from fossil fuels with renewable energy sources, this is not as easy for the pyrolysis process, as disposal of gaseous waste is a big challenge. As a result, a zero-emission economy based on chemical recycling seems to be impossible.

Under a fossil-free industry, all new plastic has to be produced from biogenic resources. Since the amount of biogenic resources are very limited and many parts of the industry rely on it, this cannot be covered by organic waste alone. Already today, food, feed, and fuel consumption compete for biomass. To avoid increasing the global hunger problem and biodiversity losses from industrial agriculture, the carbon gap for new plastic packaging must be reduced - not only by lowering the total amount of packaging, but also by reducing losses during recycling processes. As demonstrated in this report, one way to reduce carbon loss is the shift from chemical to mechanical recycling, as

[33] EDGAR, *GHG emissions of all world countries*, 2021

the losses for mechanical recycling are comparably lower (31% compared to 53% for mechanical and chemical recycling, respectively).

Efforts to develop commercial chemical recycling of plastic can be traced back at least to the 1970s.[34][35] Since then, the concept seems to have stagnated in terms of practical applications on a large scale. No evidence outside of small-scale demonstration projects has been found to support current industry claims about the technical effectiveness of chemical recycling. There are many theoretical approaches and proposals, but little to no evidence that they can actually be put into practice. It is known from expert interviews that the pyrolysis plants used industrially to date usually receive a standardised[36] feed from post-industrial packaging waste or plastic streams without cross-contamination from other waste streams. However, the resulting pyrolysis oil is only used in very small quantities in steam crackers to prevent disturbing the process running with crude oil distillates. The current attempt to use non-standard mixed plastic waste in pyrolysis on a large scale faces extreme challenges. Currently, there is no known (semi-)industrial pyrolysis plant that produces relevant quantities of chemically recycled plastic from mixed plastics.[37,38,39]

The numbers used in this report taken from published LCAs are based only on assumptions from chemical companies active in the field of pyrolysis and, therefore, give an idealised picture. However, even with these figures, the results clearly show that pyrolysis is inferior to mechanical recycling for the recycling of plastic waste in terms of a carbon-neutral economy.

To actually achieve a circular and carbon-neutral economy, further innovations are needed to increase the circularity of plastic packaging, thus reducing the amount of plastic waste that cannot be mechanically recycled. Pyrolysis should only be possible as the last option and should only be used for mixed plastic waste that can neither be avoided nor mechanically recycled. However, all steps that can be taken to reduce this stream (and plastic packaging in general) and to increase the share of mechanical recycling must have an absolute priority. All policy instruments have to reflect this approach; and a clear difference must be made between chemical recycling with all its negative impacts and mechanical recycling, which still has a lot of potential in terms of carbon neutrality (electricity mix can be completely fossil-free) and recyclability of packaging (design-for-recycling and new collection systems).

8 Conclusions

The main findings of the study are the following:

- Based on the figures from LCAs of the industry, it is shown that pyrolysis of plastic packaging causes much higher GHG emissions than mechanical recycling (pyrolysis emissions are nine times higher than mechanical recycling).

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[34] Matsumoto et al, *Development of process of fuel recovery by thermal decomposition of waste plastics. In Conference Papers of the First International Conference, Conversion of refuse to energy*, 1975

[35] Porteous, *An assessment of energy recovery methods applicable to domestic refuse disposal*, 1975

[36] Standardised means that the plastic stream consists of defined and known plastic waste of a certain reproducible specification.

[37] Rollinson al, *Chemical Recycling: Status, Sustainability, and Environmental Impacts*, 2020
Quicker 2019

[38] Lopez et al, Thermochemical routes for the valorization of waste polyolefinic plastics to produce fuels and chemicals - A review, 2017

[39] Quicker, P. Evaluation of recent developments regarding alternative thermal waste treatment with a focus on depolymerisation processes, 2019

- The carbon efficiency of pyrolysis is very low, meaning that over half of the carbon in plastic is lost in the process and has to be replaced by new plastic.
- Combining mechanical and chemical recycling to process plastic waste to recyclate prevents GHG emissions compared to the use of primary plastic.
- Mechanical recycling must be prioritised over pyrolysis wherever possible. Measures such as design for recycling and other innovations must be incentivised in order to achieve this goal.

If a pyrolysis industry is established in the coming years, this will affect the possibilities for treating plastic in the future. Once a plant is built, it needs raw materials. For as long as regulations do not introduce safeguards, the industry will use the cheapest and most easily recyclable material available (feedstock that can be actually recycled through mechanical recycling). Without adequate regulations, efforts to design for recycling or other measures to strengthen mechanical recycling will be severely hampered. Legal equality of chemical and mechanical recycling processes for packaging waste must therefore be prevented. As such, the climate impact of different recycling technologies should be considered when setting targets for recycled content.

Last but certainly not least, it is important to reduce the overall amount of packaging to lower the GHG emissions in this sector - it is not possible to achieve a zero-emission economy by recycling alone.

9 Annex

9.1 Mass flows

Table 6 Estimated Output Capacity Requirements for 2030 (ktonne) as published by Eunomia 2020

Technology	Chemical				Physical	
	Thermal (Primarily pyrolysis)		Chemical Depolymerisation (primarily PET)		Mechanical plus dissolution	
Level Material	Med	Amb	Med	Amb	Med	Amb
Polyolefins	649	1.487	-	-	868	1.330
PET	-	-	86	232	30	41
Other (PS,PVC etc)	503 - 726					

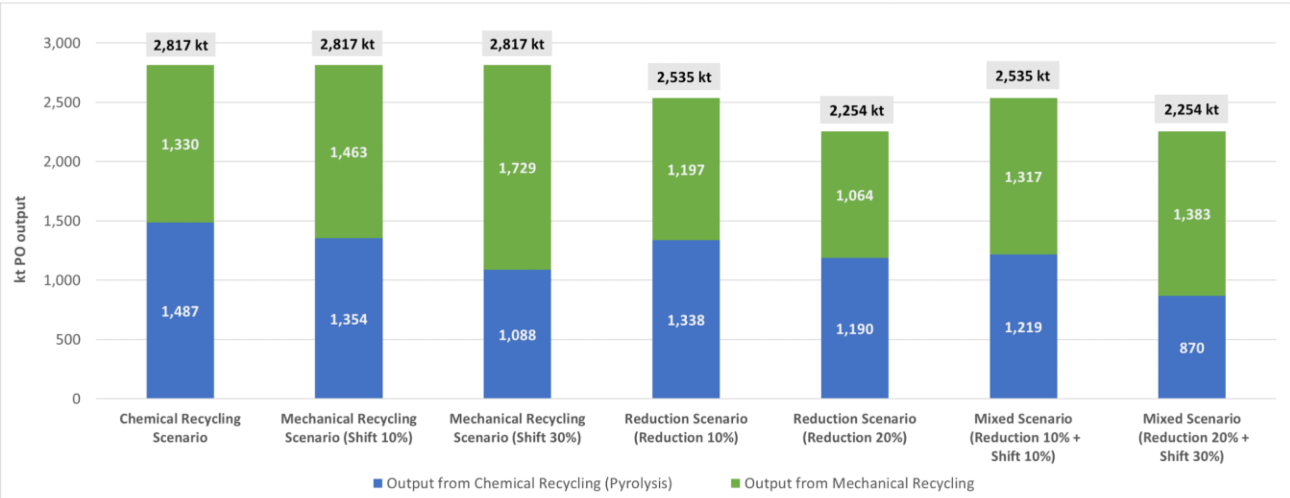

Figure 5 Output quantities from chemical recycling (pyrolysis) and mechanical recycling for the different scenarios – Based on the ambitious scenario from Eunomia (2020) (own representation)

9.2 GHG emissions results

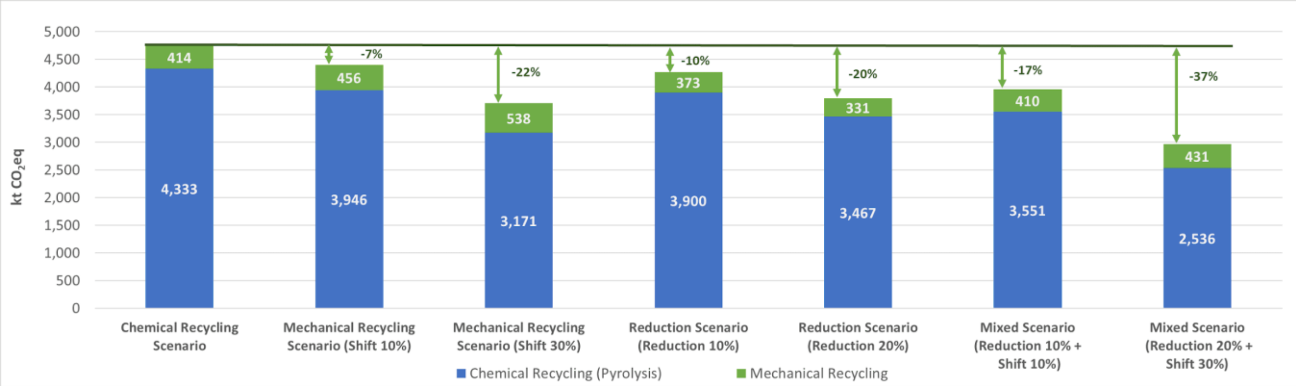

Figure 6 GHG emission results - Based on the ambitious scenario from Eunomia (2020) (own representation)

9.3 Calculation of credits and net result

Table 7 shows the burdens for the recycling process, the credits for replaced primary plastics and the net result (burdens minus credits). A negative net result means that the entire system (burdens and credits) leads to a total climate mitigation, as mechanical recycling causes fewer GHG emissions than the production of the primary plastic would.

Table 7 Burdens for the recycling process, the credits for replaced primary plastics and the net result

kg CO_2eq/kg plastics output	**Pyrolysis**	**Mechanical Recycling**
Burdens	2.91	0.31
Credits (1)	2.30	1.84
Net result	0.62	-1.52

(1) credit for 50% PE and 50% PP; data for credits from ecoinvent[40]

[40] https://ecoinvent.org/

9.4 Carbon efficiency

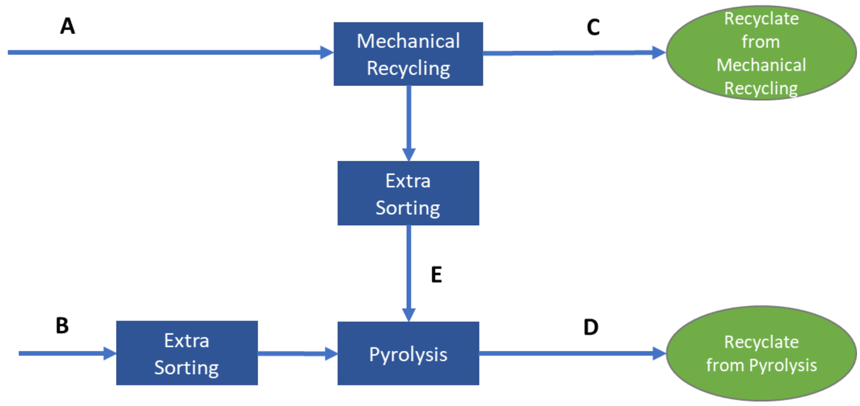

Figure 7 Illustration of the variables of formula 1

10 Acknowledgements

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