Monitoring chemical recycling

How to include chemical recycling in plastic recycling monitoring?

CE Delft

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This report was prepared by:
Martijn Broeren, Meis Uijttewaal and Geert Bergsma

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Further information on this study can be obtained from the contact person Geert Bergsma (CE Delft)

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Management summary

To reach environmental goals regarding climate change and the circular economy, the recycling rate of plastics has to increase considerably over the coming years.
The Netherlands aims to cover 40% of its plastics demand with recycled material by 2030 (I&W/EZK, 2018). The current recycled content of plastics is 9%.

The increase in plastics recycling is expected to come primarily from mechanical recycling. However, a considerable contribution is also expected from new ('chemical'[1]) recycling technologies. These new technologies are more complex and can be more integrated in chemical production sites. It is therefore less obvious how their recycling performance can be monitored. The Dutch Ministry of Environment has requested CE Delft to investigate how chemical recycling can be integrated in existing monitoring systems for recycling.

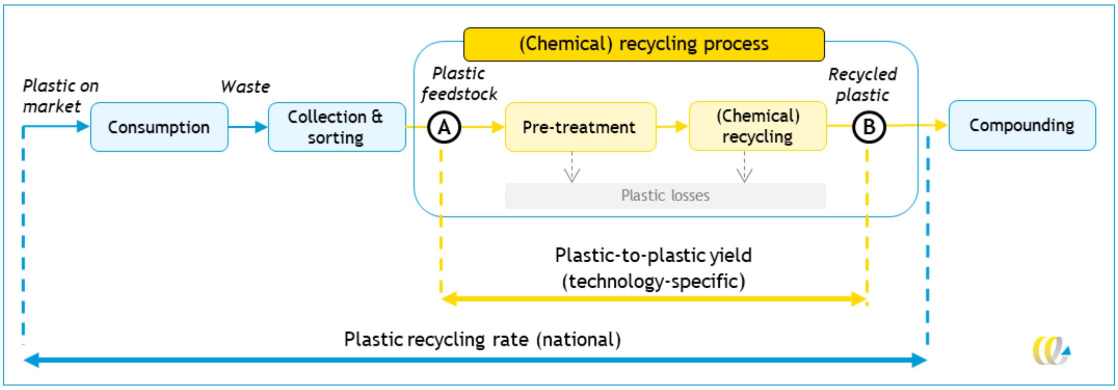
This study shows that the yield of chemical recycling technologies can be calculated similarly to how the yield of mechanical recycling is calculated. While chemical recycling technologies are more complicated and typically involve more process steps to produce recycled plastics than mechanical recycling, the same main principles can be used.

To assess the plastic losses in different recycling chains and enable a uniform monitoring system, a 'plastic-to-plastic yield' is proposed in this report (see Figure 1). We define the plastic-to-plastic yield of a recycling technology as the amount of new plastic that can be produced from plastic waste sent to recycling (i.e. a weight share).

The concept of the plastic-to-plastic yield can be applied to a specific (chemical) recycling technology to estimate to what extent it contributes to the supply of recycled plastics.

In addition, we derive indicative 'default' plastic-to-plastic yields for reference, using input from technology developers and chemical companies. These include solvent-based extraction (PS), depolymerisation (PET) and pyrolysis (mixed plastic waste to polyolefin plastic). For gasification of mixed plastics, only a first, uncertain yield could be derived.

Figure 1 - Definition of plastic-to-plastic yield



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[1] The term 'chemical recycling' is used here as a shorthand to refer to a range of novel technologies. However, it should be noted that solvent-based extraction is not always considered a form of chemical recycling.

The default plastic-to-plastic yields are high for solvent-based extraction and depolymerisation (97-100%). Furthermore, recycled material can be tracked throughout these processes. There is no mass balance approach necessary. The monitoring principles used for mechanical recycling can also be applied to these technologies.

For pyrolysis, which is a more complex process, there are more differences compared to mechanical recycling. Firstly, this process needs more energy. We checked whether this energy demand should be included in the plastic-to-plastic yield and conclude that this is not necessary. This energy requirement is met by combusting gases that are produced from the waste plastic input during pyrolysis and this is reflected in the lower plastic-to-plastic yield. Secondly, the main pyrolysis output (pyrolysis oil) can be blended with fossil naphtha in a chemical production site. This means the recycled material is distributed over several products and that a mass balance approach is necessary to calculate the plastic-to-plastic yield. In this report we conclude that the 'fuels exempt' mass balance approach results in a plastic-to-plastic yield for pyrolysis of about 49%. This factor also roughly corresponds with the CO_2 emission reduction of pyrolysis relative to mechanical recycling.

Extended producer responsibility (EPR) organisations (such as the Dutch Packaging EPR organisation Afvalfonds Verpakkingen) can ask chemical recycling companies to apply the methodology described in this report to calculate a company-specific plastic-to-plastic yield. Together with a verification by a third party, the indicative default plastic-to-plastic yields derived can be used to check the yields reported by companies.

The analysis results in the following recommendations:
- For all technologies, including mechanical recycling, a more accurate view on which waste plastic feedstocks (amounts and compositions) are available is required.
  In addition, it would be helpful to obtain more specific information on which waste plastic streams are actually processed in each technology (i.e. shares of different polymer types, moisture, dirt, other materials) and to better understand the feedstock limitations of each technology.
- As the majority of the technologies included in our analysis are not yet operating at full scale, we expect that technological developments will occur quickly. Therefore, we advise that the default plastic-to-plastic yields are revisited within two to three years.
- It is helpful to set up mass balance rules at the European level, and avoid a situation in which individual member states set up different rules. This limits costs for industry, but is also more consistent for consumers.
- We suggest to gather more precise data for gasification to reduce uncertainties.
- This study focusses on recycling plastic waste to new plastics. One could argue that recycling plastics to other (non-plastic) materials such as cosmetic ingredients or solvents should also count as recycling (i.e. based on plastic-to-material yields instead of plastic-to-plastic yields). Further research would be required to determine these factors.

The plastic-to-plastic yields do not represent all aspects that should be taken into consideration when developing more sustainable plastic waste treatment systems. Other aspects include greenhouse gas emissions or energy use of technologies, how much upfront sorting is required for a particular technology, optimal waste plastic collection, design for recycling, whether technologies can co-process mixed waste streams, costs, quality/value of product outputs, etc. The future design of plastic waste collection, sorting and recycling systems for a circular economy should account for these various practical, environmental and economic aspects of the available technologies.

Managementsamenvatting

Om milieudoelstellingen op het gebied van klimaatverandering en de circulaire economie te halen, zal het recyclingpercentage van plastics aanzienlijk moeten toenemen in de komende jaren. Nederland heeft voor 2030 als doel om 40% van de vraag naar plastics te dekken met gerecycled materiaal (I&W/EZK, 2018). Op dit moment bestaan plastics voor 9% uit gerecycled materiaal.

De toename in plasticrecycling wordt naar verwachting met name met mechanische recycling gerealiseerd. Er wordt echter ook een aanzienlijke bijdrage verwacht van nieuwe (‘chemische’[2]) recyclingtechnologieën. Deze technologieën kunnen complexer zijn en kunnen worden geïntegreerd in bestaande chemische productielocaties. Hierdoor is het monitoren van hun recyclingprestaties ingewikkelder. Het Nederlandse Ministerie van Infrastructuur en Waterstaat heeft CE Delft daarom gevraagd te onderzoeken hoe chemische recycling kan worden geïntegreerd in bestaande monitoringssystemen voor recycling.

Deze studie laat zien dat het massarendement (de *yield*) van chemische recycling op dezelfde manier kan worden berekend als bij mechanische recycling. Hoewel de technologieën voor chemische recycling complexer zijn en doorgaans meer processtappen met zich meebrengen, kunnen dezelfde hoofdprincipes toegepast worden.

Om de verliezen van plastic die optreden in verschillende recyclingketens in te schatten en een uniform monitoringsysteem mogelijk te maken, wordt in dit rapport een ‘plastic-naar-plastic-rendement’ voorgesteld (zie Figuur 1). We definiëren het plastic-naar-plastic-rendement van een recyclingtechnologie als de hoeveelheid nieuw plastic die geproduceerd kan worden uit een hoeveelheid afgedankt plastic die naar de recyclingtechnologie gestuurd wordt (dat wil zeggen een massa-aandeel).

Het concept van het plastic-naar-plastic-rendement kan worden toegepast op specifieke (chemische) recyclingtechnologieën om in te schatten in hoeverre deze bijdraagt aan het aanbod van gerecyclede plastics.

Daarnaast leiden we indicatieve ‘standaardwaardes’ voor het plastic-naar-plastic-rendement af ter vergelijking, op basis van informatie van technologieontwikkelaars en chemische bedrijven. Hierbij gaat het om selectieve extractie (PS), depolymerisatie (PET) en pyrolyse (gemengd plastic afval naar polyolefinen). Voor vergassing van gemengd plastic afval kon alleen een grof, onzeker rendement worden bepaald.

De standaardwaarden voor het plastic-naar-plastic-rendement zijn hoog voor selectieve extractie en depolymerisatie (97-100%). Daarnaast kan het gerecyclede materiaal door deze processen getraceerd worden. Er is hierdoor geen zogeheten massabalansbenadering nodig. De monitoringsprincipes die voor mechanische recycling gebruikt worden, kunnen ook toegepast worden op deze technologieën.

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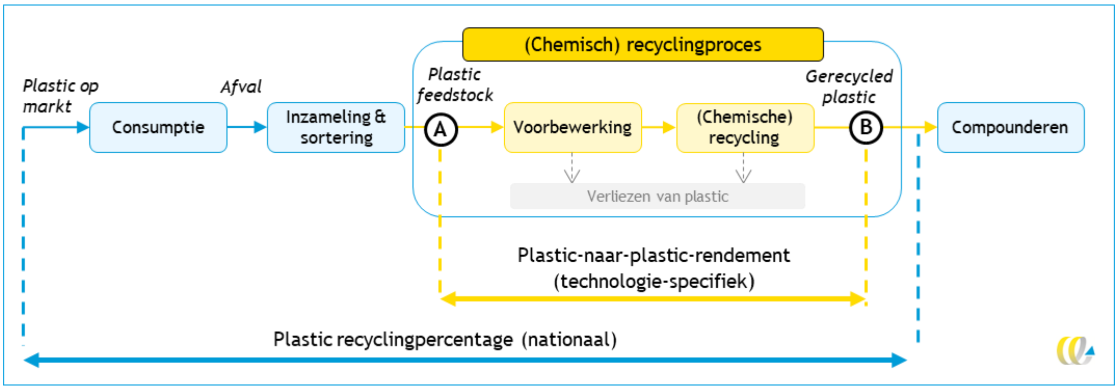
[2] De term ‘chemische recycling’ wordt hier gebruikt om naar een scala van nieuwe recyclingtechnologieën te verwijzen. Recycling op basis van selectieve extractie (‘oplossen’) wordt echter niet altijd als vorm van chemische recycling beschouwd.

Figuur 1 - Definitie plastic-naar-plastic-rendement



Pyrolyse, een complexer proces, verschilt sterker van mechanische recycling. Ten eerste gebruikt dit proces meer energie. We hebben gecontroleerd of deze energievraag zou moeten worden meegenomen in het plastic-naar-plastic-rendement en concluderen dat dit niet nodig is. De energievraag van het pyrolyseproces wordt gedekt door gassen te verbranden die tijdens het proces uit het afgedankte plastic geproduceerd worden, wat al tot uiting komt in het lagere plastic-naar-plastic-rendement. Ten tweede kan het hoofdproduct van pyrolyse (pyrolyseolie) gemengd worden met fossiele nafta in chemische fabrieken. Het gevolg hiervan is dat het gerecyclede materiaal wordt verdeeld over allerlei producten, waardoor een massabalansbenadering nodig is om het plastic-naar-plastic-rendement te bepalen. In dit rapport concluderen we dat de massabalansvariant waarin brandstoffen uitgezonderd worden (‘*fuels exempt*’) resulteert in een plastic-naar-plastic-rendement van ca. 49%. Deze factor komt ook grofweg overeen met de CO_2-emissiereductie van pyrolyse ten opzichte van mechanische recycling.

Organisaties voor uitgebreide producentenverantwoordelijkheid (UPV), zoals het Nederlandse Afvalfonds Verpakkingen, kunnen chemischerecyclingbedrijven vragen de methodologie uit dit rapport toe te passen om een bedrijfsspecifiek plastic-naar-plastic-rendement te berekenen. Samen met een verificatie door een derde partij, kunnen de standaardwaarden voor plastic-naar-plastic-rendementen gebruikt worden om de rendementen die bedrijven rapporteren te controleren.

De analyse resulteert in de volgende aanbevelingen:
- Voor alle technologieën, inclusief mechanische recycling, is het nodig om een beter beeld te ontwikkelen van welke plastic-afvalstromen beschikbaar zijn (hoeveelheden en samenstellingen). Daarnaast zou het behulpzaam zijn om meer specifieke informatie te verzamelen over welke plastic-afvalstromen daadwerkelijk verwerkt worden in elke technologie (d.w.z. aandelen van verschillende polymeersoorten, vocht, vuil, andere materialen) en om beter te begrijpen wat de beperkingen zijn van elke technologie wat betreft de afvalstromen die verwerkt kunnen worden.
- Aangezien het grootste deel van de technologieën die in onze analyse zijn meegenomen nog niet op volledige schaal operationeel is, verwachten we dat de technologische ontwikkeling snel zal gaan. We stellen daarom voor om de standaardwaarden voor de plastic-naar-plastic-rendementen opnieuw te bekijken binnen twee à drie jaar.
- Het is nuttig om massabalansregels op Europees niveau vast te stellen, en een situatie te vermijden waarin individuele lidstaten verschillende regels opstellen. Dit beperkt kosten voor de industrie, maar is ook logischer voor consumenten.
- We stellen voor om preciezere data voor vergassing te verzamelen om onzekerheden te verkleinen.

- Deze studie richt zich op het recycling van afgedankte plastics tot nieuwe plastics. Men kan beargumenteren dat ook het recyclen van afgedankt plastics naar nieuwe (niet-plastic) materialen zoals cosmetica-ingrediënten of oplosmiddelen ook zou moeten tellen als recycling (dus gebaseerd op plastic-naar-materiaal-rendementen in plaats van plastic-naar-plastic-rendementen). Meer onderzoek zou nodig zijn om deze factoren te bepalen.

De plastic-naar-plastic-rendementen geven niet alle aspecten mee die meegewogen zouden moeten worden bij het ontwikkelen van duurzamere afvalverwerkingssystemen voor plastics. Andere aspecten omvatten de broeikasgasemissies of het energieverbruik van technologieën, de mate van plastic sortering die nodig is, optimale inzameling van plastic afval, producten ontwerpen voor recycling, of technologieën gemengde afvalstromen tegelijkertijd kunnen verwerken, kosten, de kwaliteit/waarde van de producten van een recyclingtechnologie, etc. Het toekomstige ontwerp van de inzameling, sortering en recycling van plastic afval voor een circulaire economie moet rekening houden met deze praktische, milieukundige en economische aspecten van de beschikbare technologieën.

1 Summary and conclusions

This report studies how the contribution of novel (‘chemical’[3]) plastic recycling technologies to recycling targets can be monitored. To assess the plastic losses in different recycling chains and enable a uniform monitoring system, a ‘**plastic-to-plastic yield**’ indicator is operationalised and applied.

This chapter provides an overview of the research and its conclusions. Subsequent chapters provide a practical guideline (Chapter 2), more detail on monitoring (Chapter 3) and on the plastic-to-plastic yields (Chapter 4).

1.1 Introduction

To reach environmental goals regarding climate change and the circular economy, the recycling rates of materials such as metals, glass and plastic have to increase considerably over the coming years. This is especially challenging for plastics. The Netherlands aims to cover 40% of its plastics demand with recycled material by 2030 (I&W/EZK, 2018).
The increase in plastics recycling is expected to come primarily from mechanical recycling (from 275 ktonne/yr now to 750 ktonne/yr in 2030). However, a considerable contribution (250 ktonne/yr) is also expected from new (‘chemical’) recycling technologies.

European countries have national targets for their plastics recycling rate. The recycling rate for plastic packaging is for instance defined as the weight of recycled plastic packaging divided by the weight of plastic packaging waste produced (mostly estimated by calculating the weight of plastic packaging placed on the market (EU, 2005)). The Dutch ministry of Infrastructure and Water Management (I&W) would like to understand how chemical recycling technologies can contribute to the recycling goals.

The national monitoring of plastic recycling rates is further discussed in Paragraph 3.1.

The ministry has requested CE Delft to investigate how chemical recycling can be integrated in existing monitoring systems for recycling and to determine indicative plastic yields for these technologies. More specifically, the following questions are studied here:
- How can the yield of new plastics of different recycling processes be determined in a practical and reliable way?
- What is a suitable measurement point for recycling via gasification, pyrolysis, depolymerisation and solvent-based extraction?
- What are indicative plastic yields of these novel recycling technologies?
- Is Mass Balancing necessary to include chemical recycling technologies into national recycling rate monitoring? And which form of mass balancing should be used?
- Should the energy use of chemical recycling processes be included in the monitoring and how should this be done?

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[3] This report focusses on novel plastic recycling technologies such as pyrolysis, depolymerisation, solvent-based extraction (‘dissolution’) and gasification. The term ‘chemical recycling’ is used as a shorthand to refer to these technologies. However, it should be noted that solvent-based extraction is not always considered a form of ‘chemical recycling’ (e.g. by companies developing the process or by the European Coalition for Chemical Recycling), because it does not involve changing the chemical structure of the polymers in the plastic. Solvent-based extraction is increasingly considered as a form of ‘physical recycling’ or ‘material recycling’.

- How strong is the correlation between the plastic yields of chemical recycling technologies and their carbon footprint reductions compared to incineration?

1.2 Monitoring recycled plastic yields

Plastic-to-plastic yields can be used to monitor chemical recycling

The study shows that the yield (or recycling rate) of chemical recycling technologies can be determined similarly to mechanical recycling. While chemical recycling technologies are more complicated and typically involve more process steps to produce recycled plastics than mechanical recycling, the same main principles can be used. However, it is important to realise that some forms of chemical recycling can yield less plastic than others, especially when part of the plastic input is consumed to supply process energy.

To assess the plastic losses in different recycling chains and enable a uniform monitoring system, a ‘**plastic-to-plastic yield**’ indicator is operationalised and applied in this report.

National governments have different options when establishing a monitoring system for chemical recycling based on plastic-to-plastic yields:
1. Require recycling companies to derive **company-specific plastic-to-plastic yields**. These plastic-to-plastic yields should be derived using the method described in this report and be verified by an independent party. This option is discussed further in Paragraph 1.3.
2. Use conservative **default plastic-to-plastic yields** values for the technologies applied. In this report, we derive first estimates of the plastic-to-plastic yields for a number of chemical recycling systems. These are further discussed in Paragraph 1.4.
3. Let companies choose to use a technology-specific or default plastic-to-plastic yield.

Regardless of the selected option, the plastic-to-plastic yields used should be verified by an independent party.

What is the plastic-to-plastic yield?

The plastic-to-plastic yield of a recycling technology corresponds to the amount of recycled plastic (ready for compounding) that can be produced from one tonne of plastic in plastic waste sent to recycling[4]. Figure 2 illustrates the plastic-to-plastic yield and shows its relation to overall (national) recycling rates.

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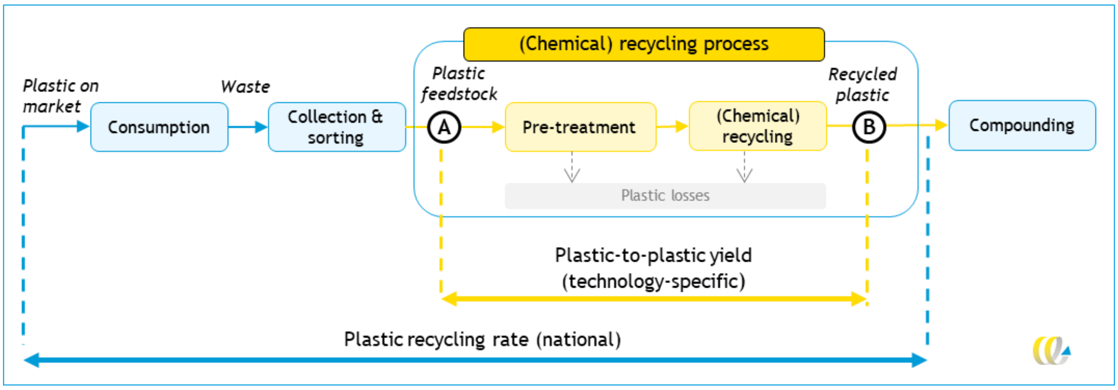
[4] The term ‘plastic in plastic waste’ is used to indicate that only the plastics present in the waste stream are counted. Other materials that can be present (moisture, sand, biomass, metals, etc.) are not counted.

Figure 2 - Definition of plastic-to-plastic yield



The plastic-to-plastic yield is defined as the mass of recycled plastic ready for compounding divided by the mass of plastic in plastic waste sent to recycling after collection and sorting. These are points A and B in Figure 2, respectively. Point A is referred to as the 'measurement point'. It lies after the collection of discarded plastics and sorting them into standardised fractions (i.e. plastic bales that meet certain specifications, such as the DKR streams in the Netherlands). These fractions can be recycled using mechanical or chemical technologies.

Point B, where recycled plastic is ready for compounding[5], is known as the 'calculation point' for recycling. All recycled material that reaches this step counts towards the national plastic recycling rate. The calculation point lies before compounding because 'recycled plastic' is defined in EU legislation as '*Plastic separated by polymers that does not undergo further processing before entering pelletisation, extrusion, or moulding operations; Plastic flakes that do not undergo further processing before their use in a final product.*' (EU, 2019).

A plastic-to-plastic yield corresponds to a particular recycling technology (or chain technologies) operating in specific conditions. The yield can be influenced by the technologies applied, the plastic feedstock used, operating conditions and downstream processing choices. For example, the plastic-to-plastic yield of a pyrolysis-based recycling chain aiming to replace fossil naphtha and to produce recycled plastics will differ from the plastic-to-plastic yield of a pyrolysis-based recycling system primarily aiming to replace fossil diesel. When discussing plastic-to-plastic yields, it is therefore important to always note its key characteristics, i.e. the technology, feedstock mix, output products, whether mass balancing is used, and other remarks if applicable.

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[5] The amount of recycled plastic ready for compounding (point B in Figure 2) typically cannot or is not measured directly (Brouwer, et al., 2019), both for mechanical and chemical recycling. However, the amount of DKR plastic sent to recycling (point A in Figure 2) can be measured. Plastic-to-plastic yields therefore serve to bridge this gap. The amount of plastic sent to a specific recycling technology (point A in Figure 2) can be multiplied with a plastic-to-plastic yield corresponding to that specific recycling chain to estimate how much recycled plastic (point B in Figure 2) will be produced.

1.3 Option 1: Deriving a company-specific plastic-to-plastic yield

It is possible to give companies the option of determining the plastic-to-plastic yield of their specific recycling chain. This should be well-documented and verified, especially if this results in a higher plastic-to-plastic yield than the 'default value'.

To determine the plastic-to-plastic yield of a specific company or technology, the following information is needed:

- A description of the feedstock at the measurement point (point A in Figure 3), including:
  - the source of the feedstock material;
  - any treatments that the feedstock material has undergone before arriving at the measurement point, such as sorting;
  - the composition of the feedstock material, including the amount of plastics in the feedstock;
  - a third party-verified statement on the origin of the feedstock material.
- A description of the calculation point (point B in Figure 3) and the output, including:
  - which plastic type(s) is produced.
- An overview of all processes that take place between the measurement point and the calculation point. This should at least mention:
  - the parties responsible for each process step (e.g. in the case of a pyrolysis-like process, the production of pyrolysis oil may be done by a different company than processing the pyrolysis oil).
- For each process step:
  - the amount of plastic that is lost, i.e. does not continue to the next step in the recycling chain;
  - the amount of plastic that continues to the next step in the recycling chain;
  - a third party-verified statement on the output (e.g. amounts, properties, quality).
- Which recycling steps make use of mass balancing. If at one or more of the process steps mass balancing[6] is used to allocate recycled content to specific outputs, a chain of custody model that fulfils the criteria of NEN-ISO 22095 that is verified by an accredited organisation should be in place[7].

The information provided by the company can be used to determine how much of the plastic per unit of feedstock (measurement point) ends up in the recycled plastic entering compounding (calculation point). The company-specific plastic-to-plastic yield is calculated by dividing the amount of recycled plastic entering compounding by the amount of plastic per unit of feedstock.

Note that only the amount of *recycled* material entering compounding is counted in the yield. Before compounding, the recycled basic chemicals may be combined with virgin chemicals during various conversion steps. For example, recycled ethylene may be reacted

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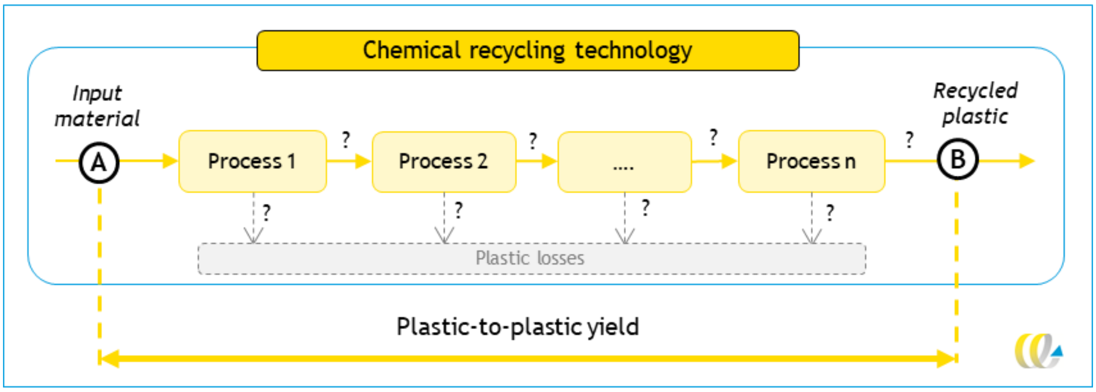
[6] Mass balancing is a bookkeeping method that is useful when virgin and recycled materials are mixed, as it enables companies to transparently keep track of and allocate recycled content to specific products. It is therefore particularly relevant for pyrolysis and gasification, since these are most likely to blend recycled and virgin product streams. More information on mass balancing can be found in Paragraph 3.3.

[7] Companies can use voluntary certification schemes for recycled content that cover the elements described above. EU CertPlast/RecyClass and GRS are examples of voluntary schemes that are used by mechanical recyclers. For convertors in Europe PolyCert Europe is an umbrella initiative to harmonise existing certification schemes. Voluntary certification schemes that are also used by chemical recyclers are for instance ISCC, RSB, RedCert and UL. The initiative by NEN to develop a generic chain of custody certification should facilitate interoperability in supply chains.

with oxygen and fossil terephthalic acid to produce (partially recycled) PET. At the calculation point (point B in Figure 3), only the recycled fraction of the plastic output is counted.

Figure 3 - Information required to determine the plastic-to-plastic yield of a recycling system



1.4 Option 2: Default plastic-to-plastic yields for chemical recycling

CE Delft shared a questionnaire and organised follow-up discussions with ten companies developing chemical recycling technologies to estimate the plastic-to-plastic yield of different recycling routes. CE Delft categorised the results into four groups of technologies gasification, pyrolysis, depolymerisation and solvent-based extraction; one company's technology could not be categorised in these groups. In addition to gathering the plastic-to-plastic yields, specific attention has been paid to understanding the uncertainties, limitations and/or conditions surrounding these yields.

Table 1 shows the plastic-to-plastic yields. These default yields can be used as a first-order estimate for policymakers, or as a reference point for companies when deriving a company-specific plastic-to-plastic yield. The full data overview per technology is shown in Annex A (including information on the use of literature or assumptions).

The default plastic-to-plastic yields derived here are described in greater detail in Chapter 4. The full data overview per technology is shown in Annex A (including information on the use of literature or assumptions).

Table 1 - Calculated indicative default plastic-to-plastic yields for (chemical) recycling systems

Technology	Input	Output	Mass balancing used	Plastic-to-plastic yield
Solvent-based extraction	EPS[a]	PS	No	100%
Depolymerisation	DKR 328	PET	No	97%
Pyrolysis	DKR 350 (mixed plastics) and DKR 310 (foils)	PE	Yes, 'fuels exempt'	49%
Gasification	Mixed plastics[a]	PE/PP	Yes, 'fuels exempt'	34%[b]

a) These values correspond to EPS from deconstruction waste and a 'custom' mix of DKR and non-DKR plastic streams. While the plastic-to-plastic yield definition focusses on the use of DKR streams as a measurement point, the same principle can be applied to other plastics streams. When comparing different recycling options for the same waste plastic stream, care should be taken that the measurement point is identical, i.e. that the same plastic compositions/purities are used.

b) Uncertain value for route to polyolefins, see 'Data accuracy' in Paragraph 1.5.

Important remarks regarding the indicative plastic-to-plastic yields

- The plastic-to-plastic yields measure the amount of new plastic (ready for compounding and conversion) that can be produced from waste plastic leaving the collection/sorting processes. Any non-plastic material (e.g. biomass, moisture, dirt) in the input is not taken into account. Similarly, non-plastic outputs (e.g. fuels, chemicals that are not converted to plastics) are not counted.
- The plastic-to-plastic yields are indicative values, derived from information provided by companies based on the current performance and expectations of their technologies (Chapter 4). The yields will change for instance if the technologies are developed further, are scaled up, or use a different feedstock as input; the values in Table 1 are only valid for the conditions stated (inputs, outputs) and based on information gathered in late 2021. Nevertheless, note that the definition of the plastic-to-plastic yield can be applied to any recycling system.
- The plastic-to-plastic yields in Table 1 are not intended for direct comparisons across the technologies. The technologies can process different input material, which means that they cannot be compared directly.
- The values for pyrolysis and gasification are based on ‘fuel exempt’ mass balancing (see discussion in Paragraph 3.3). The plastic-to-plastic yields can change if a different form of mass balancing is used.
- The plastic-to-plastic yields do not represent all aspects that should be taken into consideration when developing more sustainable plastic waste treatment systems (e.g. greenhouse gas emissions or energy use of technologies, how much upfront sorting is required for a particular technology, optimal waste plastic collection, design for recycling, whether different technologies can co-process mixed waste streams, costs, quality/value of product outputs, etc.). Each technology has its own benefits and potential role in a circular plastic system which cannot be judged only by considering the plastic-to-plastic yield.

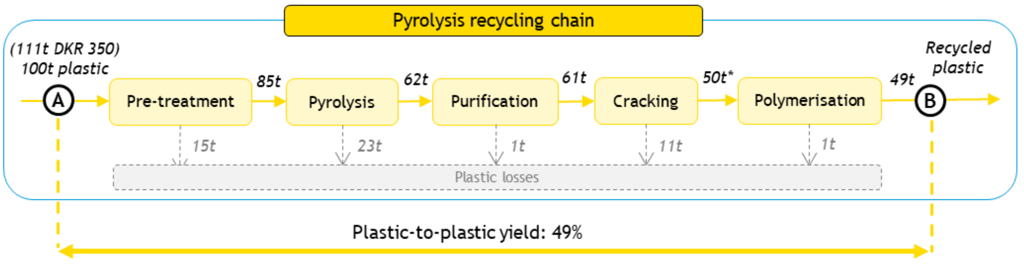
The boxes below provide practical examples of how plastic-to-plastic yields are derived for pyrolysis of DKR350 into PE, depolymerisation of PET and solvent-based extraction of PS.

Example: pyrolysis of DKR 350 into PE

In this example we illustrate how the plastic-to-plastic yield can be used to estimate the amount of recycled plastic at the calculation point.

In this case DKR 350 (mixed plastic waste) is treated with a pyrolysis technology, as illustrated in Figure 4. Since pyrolysis works best with polyolefin plastic like polyethylene (PE) and polypropylene (PP), unwanted plastic types and other materials are first removed in a pre-treatment step. The plastics are then sent to pyrolysis, which produces pyrolysis oil (as well as pyrolysis gas, which is used as a fuel). The pyrolysis oil is purified so that it can be combined with petrochemical naphtha in a steam cracker. Steam cracking produces a range of chemicals, including ethylene which can be polymerised to produce recycled PE. In this example, the producer uses mass balancing to allocate the recycled content to the ethylene/PE output.

Figure 4 - Breakdown of the plastic-to-plastic yield of a pyrolysis recycling chain targeting PE production from DKR 350



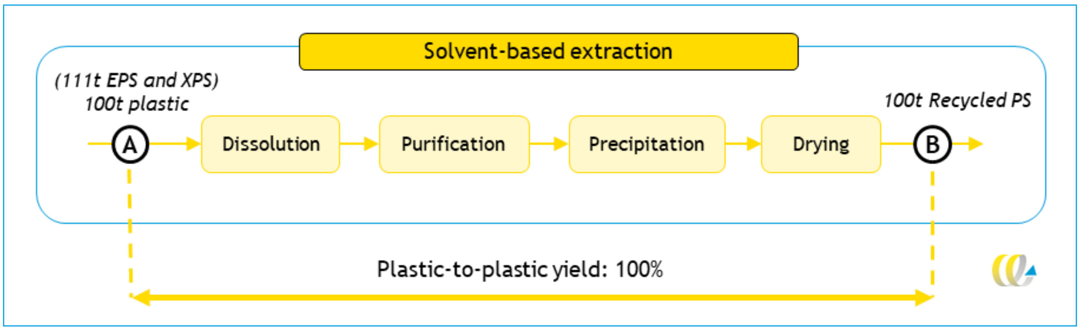
**Mass balancing is used to allocate recycled content to plastic output.*

- The plastic-to-plastic yield derived for this pyrolysis recycling system is applicable if:
  - the feedstock is DKR 350;
  - the recycling chain targets the production of new polyethylene plastics (and not fuels);
  - the ‘fuels exempt’ mass balancing method is used to allocate the recycled content to the plastic precursors.
- At the measurement point the amount of plastic in the feedstock is measured. DKR 350 may contain a maximum of 10% non-plastics. Therefore, 111 tonne DKR 350 contains at least 100 tonne plastic.
- In the pyrolysis recycling chain the plastic waste undergoes several treatment steps. During each step a certain amount of plastic is lost (see Figure 4). In total 51% of the plastic input is lost, which means that the plastic-to-plastic yield is 49%. Note that the values shown here are derived from company and literature information (see Annex A.2).

Example: Solvent-based extraction of EPS and XPS waste into PS

Expanded polystyrene (EPS) and extruded polystyrene (XPS) foam is used in insulation material in buildings. EPS and XPS can be recycled using solvent-based extraction. This process consists of several steps. First, the PS foam is dissolved. Second, in the purification step, filtration is used to remove solid impurities. In the third step, the dissolved PS is transformed into a gel. Finally, the PS gel is dried and granulated.

Figure 5 - The plastic-to-plastic yield of solvent-based extraction process targeting PS from EPS and XPS.

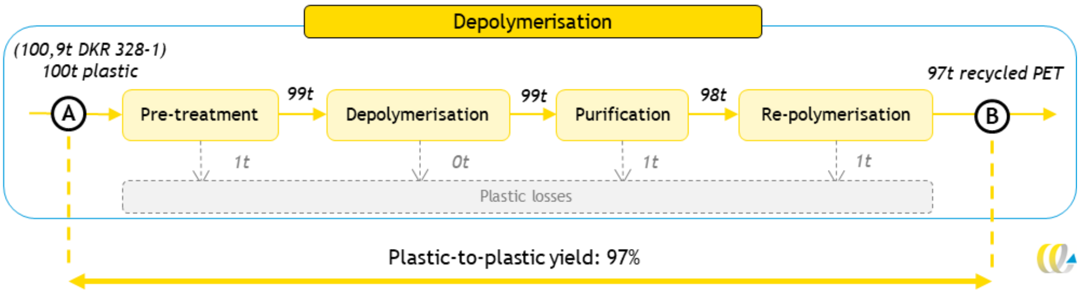


- The plastic-to-plastic yield derived for this recycling system based on solvent-based extraction is applicable if the feedstock is EPS and XPS insulation waste.
- In the solvent-based extraction process the plastic waste undergoes several treatment steps. No plastic losses occur during these steps, so the plastic-to-plastic yield is 100% . Note that the values shown here are derived from company information (see Annex A.2).

Example: Depolymerisation of DKR 328-1 into PET

In this case DKR 328-1 (sorted PET) is treated with a depolymerisation technology, as shown in Figure 6. Firstly, during the pre-treatment step impurities, moisture and volatile components are removed from the PET flakes. Next, the polyethylene terephthalate (PET) molecules are depolymerised into monomers. In the purification process, other polymers and colours are removed. Also, a small amount of PET is lost in the purification step. Finally, the monomers are re-polymerised into PET polymers, which are granulated and stored.

Figure 6 - Breakdown of the plastic-to-plastic yield of a depolymerisation recycling chain targeting PET production from DKR 328-1



- The plastic-to-plastic yield derived for this depolymerisation recycling system is applicable if the feedstock is DKR 328-1.
- In the depolymerisation recycling chain the plastic waste undergoes several treatment steps. During each step a certain amount of plastic is lost (see Figure 6). In total about 3% of the plastic input is lost, which means that the plastic-to-plastic yield is 97%. Note that the values shown here are derived from company and literature information (see Annex A.2).

1.5 Discussion

Data accuracy of the default yields

The plastic-to-plastic yields derived in this study (Paragraph 4.3) are indicative values for the current status of specific recycling chains (i.e. pyrolysis of DKR350/DKR310 to PE, depolymerisation of PET and solvent-based extraction of EPS). For gasification of mixed waste, further research is required[8]. The plastic-to-plastic yields can be used in the coming period to estimate how specific recycling chains can contribute to the production of recycled plastics.

Nevertheless, it is relevant to keep updating the plastic-to-plastic yields. This can not only provide additional verification of the yields for the recycling chains studied here, it can also be used to derive indicative plastic-to-plastic yields of other recycling chains (new technologies, different feedstocks, etc.). For example, it is possible to analyse gasification technologies in greater detail in the short term (e.g. 2022) and update the yields for the other recycling chains later on (e.g. 2024).

Role of mass balancing

More information on mass balancing can be found in Paragraph 3.3.

The plastic-to-plastic yield derived for pyrolysis and gasification here are based on mass balancing. Mass balancing can lower the barriers for plastic recycling, as recycled material can gradually be fed into existing chemical infrastructure. It enables companies to market a small share of their outputs as ‘contains 100% recycled content allocated via mass balancing’, instead of marketing all products as (for example) ‘contains 2% recycled content’.

However, it is important to keep in mind that mass balancing should always be done transparently. In the case of plastic-to-plastic yields it should always be clear whether the yield is based on mass balancing or not. In addition, it should be understood that government policies can set the rules for mass balancing. If governments decide that specific mass balancing options (e.g. ‘fuels exempt’) are no longer allowed to count towards recycling targets, this will also affect the plastic-to-plastic yields.

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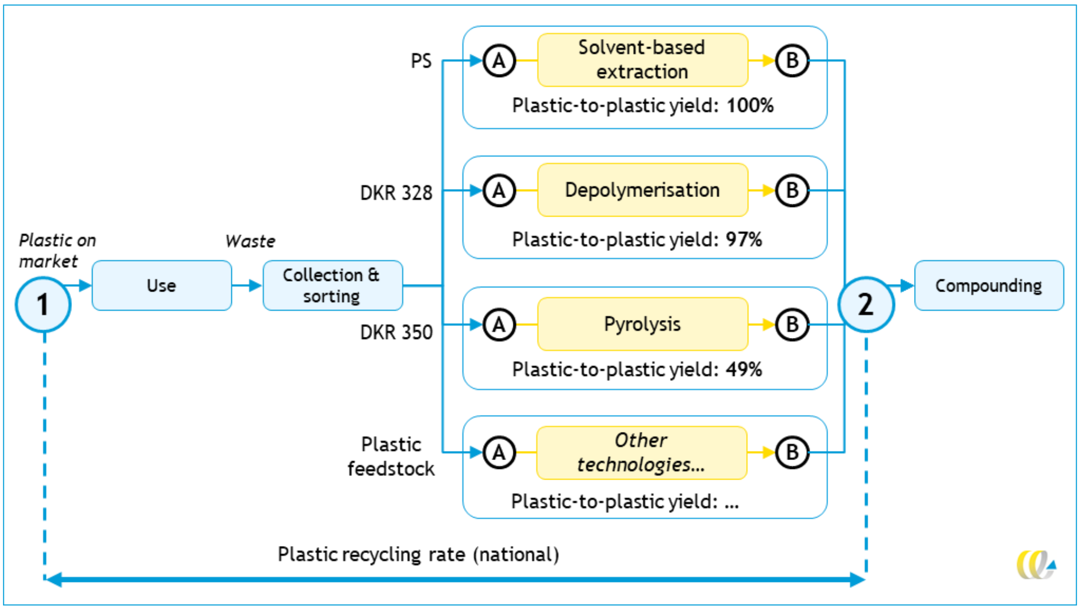
[8] For pyrolysis of DKR350/DKR310 to PE, a large set of companies provided input. Despite considerable differences between these parties, the resulting plastic-to-plastic yields are very comparable. For depolymerisation of PET and solvent-based extraction of EPS, fewer sources were available. However, these recycling chains are comparatively straightforward and have been studied in in-depth life cycle assessment (LCA) studies.
For gasification, the available information is more limited. More details on the results per company are available in Annex A.

Comparing national recycling targets and plastic-to-plastic yields

Figure 7 shows the relationship between the overall (national) plastic recycling rate and the (technology-specific) plastic-to-plastic yields. The plastics recycling rate refers to the ratio of total amount of recycled plastic, ready for compounding (point 2 in Figure 7), and the total amount of plastic put on the market in a given year (point 1 in Figure 7).

The plastic-to-plastic yields are specific to a certain recycling chain. They refer to the ratio of the amount of recycled plastic, ready for compounding, produced (points B in Figure 7) and the amount of sorted plastic sent to the technology (points A in Figure 7).

Figure 7 - Relationship between national recycling targets and technology-specific plastic-to-plastic yields



Correcting yields for energy use of recycling

A variation of the plastic-to-plastic yield, which also takes into account the (primary) energy consumption of different processes, is explored in Paragraph 4.4.1. This approach can potentially more accurately evaluate the environmental performance of the recycling systems. However, when comparing the 'material and energy' yield for mechanical and chemical recycling technologies, we find the results do not change dramatically compared to the default plastic-to-plastic yield. Although pyrolysis in particular uses considerably more energy than mechanical recycling, this energy demand is met by the losses of plastic in the process. There is therefore no need for an additional, external source of energy.
It can be noted that the energy use of technologies is less precisely documented than the (mass) yields and including energy uses complicates the calculations.

Correlation with CO_2 emission reduction

We also investigate in Paragraph 4.4.2 to what extent the plastic-to-plastic yields derived here correlate to carbon footprint results from prior life cycle assessment research. For each technology, we analysed the (net[9]) carbon footprint reductions compared to incineration of the same materials in a municipal solid waste incinerator (MSWI).

Overall, the highest carbon footprint reductions are achieved by mechanical recycling of mono-material streams and solvent-based purification/depolymerisation. These also have the highest plastic-to-plastic yields (an exception being mechanical recycling of LDPE foils). These technologies are followed by mechanical recycling of mixed plastic (reduction of about 2 kg CO_2 eq./kg waste input), which has a substantially lower plastic-to-plastic yield as well. Finally, pyrolysis/gasification result in the lowest carbon footprint reductions and also have the lowest plastic-to-plastic yields. Therefore, there seems to be a substantial correlation between the plastic-to-plastic yields and the CO_2 emission reduction. However, this can be revisited as more detailed carbon footprint information for specific technologies becomes available.

Considering the value or quality of the output material

The economic value or quality of the recycled materials produced is not included in the plastic-to-plastic yields. This is the same as for mechanical recycling. However, the criterium for recycled material in this study is that is can replace fossil based virgin plastic. This criterium means that we use a minimum quality in the monitoring. And it is good to know that this minimum quality of chemical recycling is higher than the minimum which is currently used for mechanical recycling. For mechanical recycling also producing mixed plastic material that replaces wood or concrete in the building sector is counted as recycling.

Recycling plastic into other (non-plastic) products

This report focusses on recycling discarded plastics into new plastic products. This is due to the definition of recycled plastics (as material ready for compounding) and corresponds to the need to close the plastic cycle. However, discarded plastics can also be recycled into other valuable products, including a wide range of chemical sector outputs (e.g. resins, cosmetics ingredients, solvents, lubricants, etc.) or fuels. Such applications can also avoid the conventional (petrochemical) production of such products and result in CO_2 emission reductions. These possibilities can be considered in future updates of the recycling directives.

1.6 Recommendations and outlook

Based on discussions with recycling technology developers, sorters, policymakers, extended producer responsibility (EPR) organisations and other stakeholders, some further recommendations can be derived:

- For all technologies, including mechanical recycling, a more accurate view on which waste plastic feedstocks (amounts and compositions) are available is required. In addition, it would be helpful to obtain more specific information on which waste

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[9] The comparison is based on the ‘net’ carbon footprint reduction, taking into account direct emissions from the processes, energy use, credits for products substituting conventional production processes, etc.

plastic streams are actually processed in each technology (i.e. shares of different polymer types, moisture, dirt, other materials) and to better understand the feedstock limitations of each technology.
- As the majority of the technologies included in our analysis are not yet operating at full scale, we expect that technological developments will occur quickly. Therefore, we advise that the default plastic-to-plastic yields are revisited within two to three years.
- It is helpful to set up mass balance rules at the European level, and avoid a situation in which individual member states set up different rules. This limits costs for industry, but is also more consistent for consumers.
- In our view, ‘fuels exempt’ mass balancing represents a reasonable compromise in between very strict and very lenient rules (as discussed in Paragraph 3.3.3). The plastic-to-plastic yields derived using ‘fuels exempt’ mass balancing correlate with the carbon footprints of the technologies. Furthermore, it provides some freedom for companies to attribute recycled content. This helps to make chemical recycling more viable and can enable a faster rollout of technologies that can convert difficult plastic waste streams to new products and reduce climate change impacts. Simultaneously, ‘fuels exempt’ prevents the shifting of recycled content from fuels to plastics (which is allowed under ‘free allocation’). This means recycled content that comes from plastic waste stays in products not intended for combustion, which aligns with circular economy principles. It further stimulates companies to maximise the product (i.e. non-fuel) outputs of their processes.
- We suggest to gather more precise data for gasification to reduce uncertainties.
- In this report we focused on plastic waste which is recycled to new plastics. One could argue that recycling plastics to other (non-plastic) materials such as cosmetic ingredients or solvents should also count as recycling (i.e. based on plastic-to-material yields instead of plastic-to-plastic yields). Further research would be required to determine these factors.

This study focusses on how to estimate and monitor how new recycling technologies can contribute to an increased supply of recycled plastics. The plastic-to-plastic yield operationalised here can help to develop more circular plastic systems by indicating how efficient different technologies are. Plastic-to-plastic yields should ultimately be maximised to limit the need for new resource extraction in a circular economy.

Nevertheless, the plastic-to-plastic yields are only one part in the larger puzzle of developing more circular production and consumption systems for plastics. Technologies with a lower plastic-to-plastic yield do not need to be discarded if they have other benefits. For example, novel (chemical) recycling technologies can offer other potential benefits such as feedstock flexibility or the potential to recycle plastics into different product categories. Some technologies may have a higher carbon footprint and/or energy use, but can tackle more challenging waste streams or add more value to discarded plastic than mechanical recycling.

Key differences between mechanical and novel recycling technologies are discussed in Paragraph 3.2.

The design of plastic products themselves, as well as the waste collection, sorting and recycling systems for a circular economy should account for these various practical, environmental and economic aspects of the available technologies.

2 Practical guide

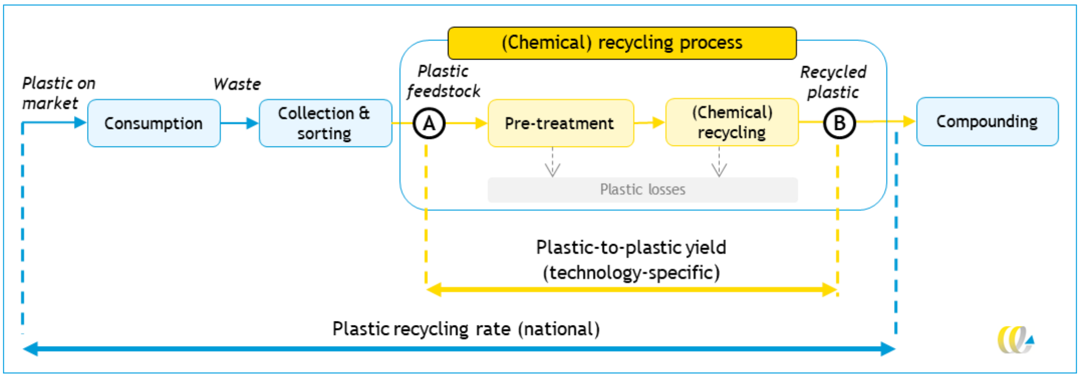
To assess the plastic losses in different recycling chains and enable a uniform monitoring system, a ‘plastic-to-plastic yield’ indicator can be used. In this practical guide, we first define the key concepts related to monitoring chemical plastic recycling. On the next page, we provide instructions on how to monitor chemical recycling using the plastic-to-plastic yield.

Measurement point
The point in the plastic recycling chain where the discarded plastic has been collected and sorted in into standardised fractions. These fractions can be recycled using mechanical or chemical technologies. At the measurement point the amount of plastic entering the recycling process can be measured. This is point A in Figure 8

Calculation point
The point where plastic separated by polymers does not undergo further processing before entering pelletisation, extrusion, or moulding operations. At this point the amount of recycled plastic cannot be measured (see discussion in Paragraph 3.1) and must therefore be calculated. This is point B in Figure 8.

Plastic-to-plastic yield
The mass of recycled plastic ready for compounding (at the calculation point) divided by the mass of plastic sent to recycling after collection and sorting (at the measurement point). A plastic-to-plastic yield corresponds to a particular recycling technology (or chain of technologies) operating in specific conditions. The yield can be influenced by the technologies applied, the plastic feedstock used, operating conditions and downstream processing choices.

Figure 8 - Definition of plastic-to-plastic yield



Instructions: Monitoring chemical recycling using plastic-to-plastic yields

To determine the total amount of recycled plastic produced by a recycling technology, you multiply the amount of waste plastic used as an input (the feedstock) with the plastic-to-plastic yield of the recycling technology. Two options for the plastic-to-plastic yield can be used:

1. Use a company-specific plastic-to-plastic yield

You collect company-specific information about the recycling system to calculate the plastic-to-plastic yield that is applicable to that specific recycling technology (or: chain of technologies).

The following steps should be used:

- Describe the feedstock at the measurement point, including:
  - the source of the feedstock material;
  - any treatments that the feedstock material has undergone before arriving at the measurement point, such as sorting;
  - the composition of the feedstock material, including the amount of plastics in the feedstock;
  - a third party-verified statement on the origin of the feedstock material.
- Describe the output of the recycling system at the calculation point, including:
  - a third party-verified statement on which plastic output is produced.
- Provide an overview of all processes that take place between the measurement point and the calculation point. This overview should at least mention:
  - the parties responsible for each process step (e.g. in the case of a pyrolysis-like process, the production of pyrolysis oil may be done by a different company than processing the pyrolysis oil);
  - the amount of plastic that is lost, i.e. does not continue to the next step in the recycling chain;
  - the amount of plastic that continues to the next step in the recycling chain;
  - which recycling steps make use of mass balancing. If at one or more of the process steps mass balancing is used to allocate recycled content to specific outputs, a chain of custody model that fulfils the criteria of NEN-ISO 22095 that is verified by an accredited organisation should be in place.

Use the provided information to determine how much of the plastic per unit of feedstock ends up in the recycled plastic entering compounding. Calculate the company-specific plastic-to-plastic yield by dividing the amount of recycled plastic entering compounding by the amount of plastic per unit of feedstock.

2. Use default plastic-to-plastic yields

Default yields have been derived for a selection of chemical recycling systems in this project.
The default yields can be used as a first-order estimate for policymakers, or as a reference point for companies when deriving a company-specific plastic-to-plastic yield. They are shown in Table 2.

The default plastic-to-plastic yields are only valid for the conditions stated.

Table 2 - Calculated default plastic-to-plastic yields for chemical recycling systems

Technology	Input	Output	Mass balancing used	Plastic-to-plastic yield
Solvent-based extraction	EPS	PS	No	100%
Depolymerisation	DKR 328	PET	No	97%
Pyrolysis	DKR 350 (mixed plastics) and DKR 310 (foils)	PE	Yes, ‘fuels exempt’	49%
Gasification	Mixed plastics	PE/PP	Yes, ‘fuels exempt’	34%

3 Monitoring of plastic recycling

3.1 Current national monitoring of plastic recycling rates

At the national level, countries monitor the (mechanical) recycling rates for plastics. The approach used to determine what counts as ‘recycled material’ has shifted over time. With the introduction of extended producer responsibility (EPR) systems for packaging, the amount of separately collected waste at consumers and/or industry was counted. This was later revised to the amount of material that was sorted and sent to recycling companies. Most recently, the calculation point was changed to the material that is actually used to make new products.

For plastic packaging in the Netherlands and other European countries, the recycling rate is defined as the weight of recycled plastic packaging divided by the weight of generated plastic packaging waste[10] (see Equation 1). Targets for the recycling rate are set in Extended Producer Responsibility (EPR) agreements between government and industry.

Equation 1

$$\text{Recycling rate} = \frac{\text{Weight of recycled plastic packaging waste}}{\text{Weight of generated plastic packaging}}$$

A key issue in determining the recycling rate is how the amount of recycled plastic packaging waste is determined. The sorted plastic bales that enter a recycling process contain dirt, moisture and other impurities that are undesirable. During recycling, these contaminants are removed and the washed plastic flakes that exit the process have a lower total weight than the sorted plastic bales that enter it. To account for these impurities, the most recent European rules (EU, 2019) require that recycling rates should be calculated based on these plastic outputs of mechanical recycling, rather than the inputs.

More specifically, the EU Commission Decisions state the *calculation point* for all materials refers to ‘*the point where waste materials enter the recycling operation whereby waste is reprocessed into products, materials or substances that are not waste, or the point where waste materials cease to be waste following preliminary treatment*’ (EU, 2019). Specifically for plastics, the Commission Decision specifies (in Annex II) the calculation point for plastics as follows: ‘*Plastic separated by polymers that does not undergo further processing before entering pelletisation, extrusion, or moulding operations; Plastic flakes that do not undergo further processing before their use in a final product.*’ In line with a recent analysis by Wageningen University and Research (Brouwer, et al., 2019), we interpret this calculation point as recycled plastics that are ready to enter a plastic compounding process. In the case of conventional mechanical recycling, these would be washed flakes.

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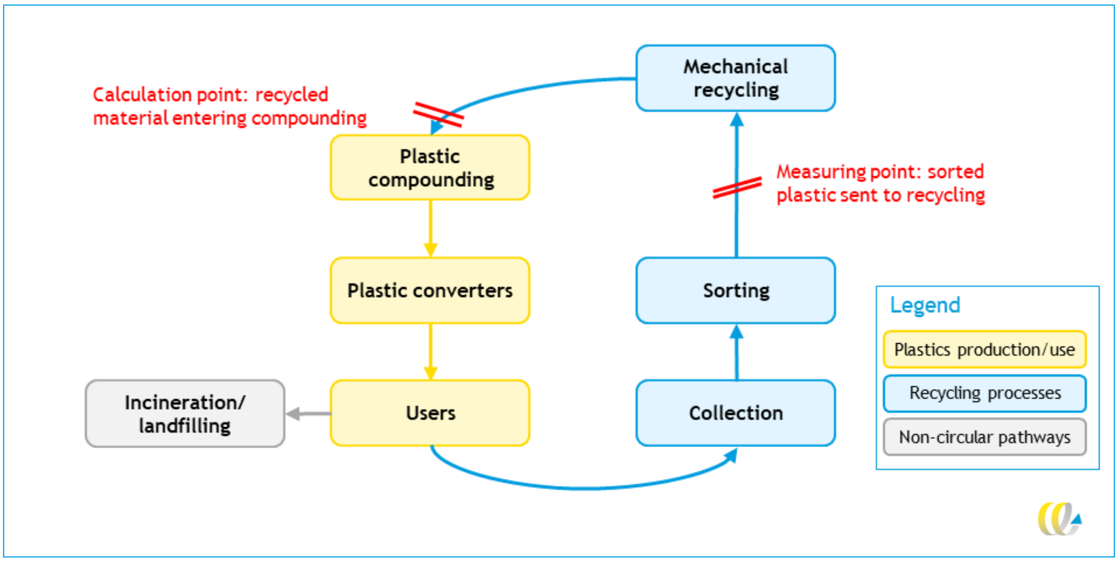
[10] According to the Commission Decision 2005/270 the “packaging waste generated in a Member State may be deemed to be equal to the amount of packaging placed on the market in the same year within that Member State” (EU, 2005).

The WUR report further notes that it is not straightforward to measure the weight of plastic packaging recycling at the calculation point. The washed flakes cannot easily be traced back to packaging. In addition, washed flakes are not always weighed since they are not necessarily traded (but processed further to granulate or a final product at the same site). The WUR authors therefore expect that the sorted bales entering mechanical recycling will be weighed (forming the *measuring point*[11]) and that the amount of washed flakes produced (at the *calculation point*) will be estimated based on typical losses and removed impurities.

Figure 9 illustrates the current plastics production/use system and the role of mechanical recycling, highlighting both the measuring point and the (new) calculation point. As noted above, the calculation point is used to determine the overall recycling rate. The weight of recycled plastic at the calculation point is derived from the sorted plastic weight measured at the measuring point, based on average loss rates.

Figure 9 - Current monitoring system for national recycling rates



Compared to existing mechanical recycling, new forms of (chemical) recycling can enable more types of plastic to be recycled and to convert them into a greater variety of products. However, chemical recycling breaks down plastics further into chemical intermediate products (e.g. basic chemicals, monomers or polymers). Therefore, more processing steps are required to return these chemical intermediates back to a compounding process (the calculation point for recycling).

The increased complexity is illustrated in Figure 9, where ‘recycling’ can refer to both mechanical or chemical recycling. For some forms of chemical recycling (e.g. pyrolysis/ gasification) the recycled intermediates can be blended with virgin materials, because they can easily be inserted into existing, primarily fossil fuel-based production chains. This makes it difficult (if not impossible) to measure the amount of recycled material at the calculation point, which has two consequences.

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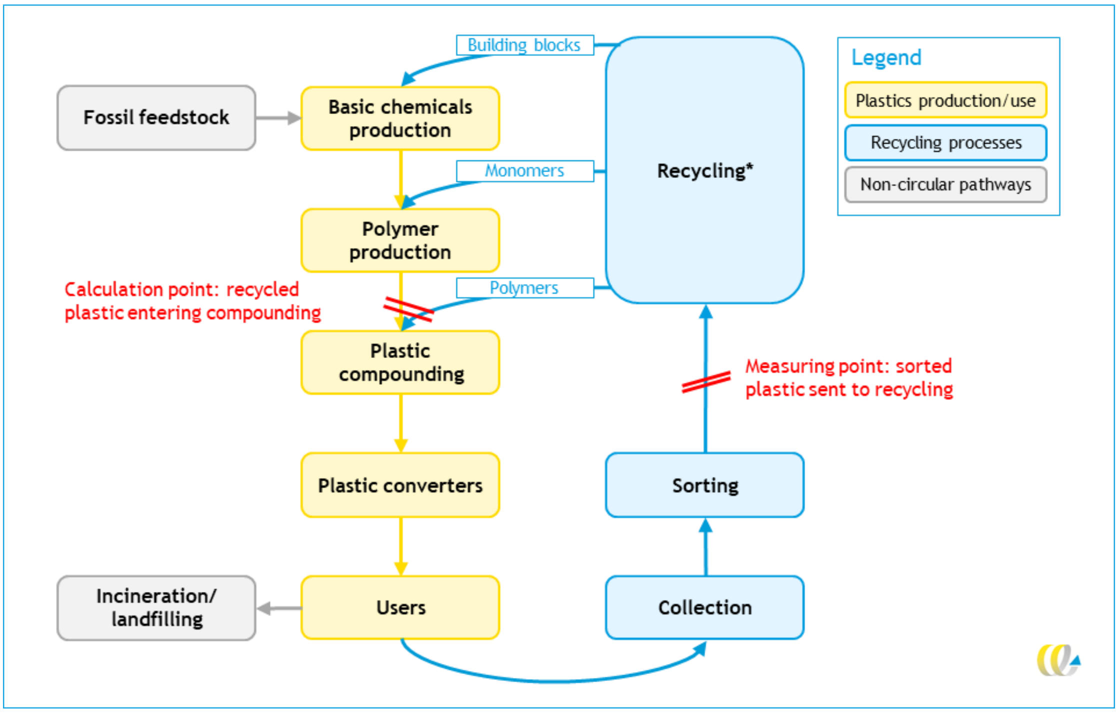
[11] In the European directive (EU, 2019), the measurement point is defined as ‘*the point where the mass of waste materials is measured with a view to determining the amount of waste at the calculation point*’.

Firstly, Mass Balance approaches are used to determine and allocate recycled content to specific products. This is further discussed in Paragraph 3.3.

Secondly, because it is not possible to measure recycled content in the products at the calculation point, it can be estimated instead. Similar to the approach used for mechanical recycling, it is likely that the measuring point for chemical recycling will be formed by the inputs of the process, i.e. the bales of sorted plastic waste entering the process (Figure 9).

It is therefore relevant to understand the typical plastic-to-plastic yields of different chemical recycling technologies, i.e. the amount of plastics produced at the calculation point when starting with a given composition at the measuring point. Due to the larger amount of processing steps involved, this can be more difficult compared to mechanical recycling. In Paragraph 4, key differences between chemical recycling and mechanical recycling are discussed in greater detail.

Figure 10 - General framework for monitoring national recycling rates



* In this framework, recycling includes all steps required to convert the input (sorted plastics) to a product ready to be used in the existing plastic production chain, i.e. to substitute fossil chemicals/polymers. All pre-treatment steps, mechanical and/or chemical processes, and final purification or upgrading steps must be included.

3.2 Considerations for chemical recycling

The variety of novel plastic recycling technologies in development introduces new complexity in measuring recycling rates. Below, we discuss the most important aspects in which novel (chemical) recycling differs from existing mechanical recycling.
These differences highlight the benefits and trade-offs that can be considered in discussions on the future role of chemical recycling in a circular plastics system. In addition, some of these aspects may affect how plastic-to-plastic yields from novel recycling technologies are calculated.

Four chemical recycling technologies

The four chemical recycling technologies considered in this study are shown in Figure 11, alongside mechanical recycling. It should be noted that this is a simplification, as companies are developing different variations of specific technologies, utilising different chemical processing, focusing on different waste plastic input types, targeting different output products, etc.

The technologies distinguished in this study are:

- **Solvent-based extraction**, in which a polymer is dissolved to be able to remove additives and contaminants from a plastic. The polymer structure itself is not affected in the process and is therefore the (main) output. It is for instance used for polystyrene (PS). No mass balance approach is needed to determine recycled content. Note that solvent-based extraction is a physical process, which is sometimes not considered part of 'chemical recycling'[12].
- **Depolymerisation**, a group of technologies in which polymers such as polyethylene terephthalate (PET) are broken down into monomers. These monomers can be used to rebuild new polymers of higher quality/purity, as polymer chain lengths can be restored and contaminants can be removed. If depolymerisation is used to directly rebuild the same polymers[13] (e.g. recycled PET from waste PET), no mass balance approach is needed to determine recycled content.
- **Pyrolysis**, which breaks down plastics such as polyethylene (PE) and polypropylene (PP) into different fractions (gas, liquid, solid). The gaseous fraction is typically burned to provide energy for the pyrolysis process. The liquid fraction ('pyrolysis oil') can resemble petrochemical refinery products such as diesel or naphtha (depending on the feedstock and pyrolysis process conditions). If it is not used as a fuel, the pyrolysis oil can substitute fossil naphtha. In this case, pyrolysis oil is typically blended with fossil materials and fed into a steam cracker, producing basic chemicals for a wide range of downstream plastic and non-plastic products. Mass balancing is required to allocate recycled content.
- **Gasification**, producing syngas (a mixture of CO and H_2) from plastic. Syngas is a basic fuel gas conventionally produced from natural gas. Among other uses, it can be converted into basic chemicals such as methanol which is used to produce various downstream plastics and non-plastic products. Since syngas and methanol are basic chemicals, they can be blended with fossil inputs, requiring mass balancing to keep track of recycled content.

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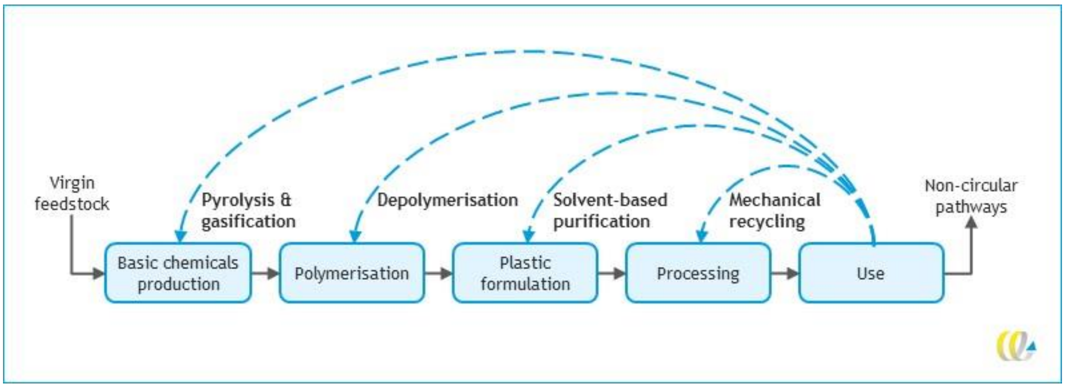
[12] Because the polymer itself does not undergo a chemical transformation during solvent-based extraction, it can be viewed as a form of mechanical recycling instead of chemical recycling. In line with Crippa et al. (2019), we consider solvent-based extraction as a form of chemical recycling here, since it is a novel recycling technology and it does affect the composition of the input plastic as a whole (e.g. polymers are separated from impurities).

[13] Alternatively, the recycled monomers could be blended with virgin monomers to build new plastics, or the monomers could be used to produce other non-plastic downstream products. In these cases, a mass balance approach could be required to allocate recycled content to specific products.

Figure 11 - Positioning of different technologies for plastics recycling. Image based on Crippa et al. (2019)



Below, we discuss the energy use of chemical recycling (which is sometimes supplied using the plastic input itself), the higher quality of its products, the increased flexibility in feedstock inputs, and the possibility to recycle plastics into other products.

Note that the last topic is related to blending recycled with virgin material streams and mass balancing, which is discussed separately in Paragraph 3.3.

3.2.1 Higher energy use and using plastics to cover energy demand

Chemical recycling processes may require substantial amounts of energy to run in comparison to mechanical recycling (see e.g. Paragaph 4.4.1). Some processes, such as pyrolysis, use a part of the waste plastic input as a fuel. Pyrolysis converts waste plastics into a mixture of solid, liquid and gaseous hydrocarbons. While the liquid fraction is used to make new products, the gaseous fraction is typically used as a fuel to supply process heat to run the process. The composition of the hydrocarbon mix can be influenced by pyrolysis process parameters such as temperature and retention time.

In the current approach to plastics recycling rates (Equation 1), a process is solely evaluated on its material yields. For pyrolysis, this means technology developers could be incentivised to maximise the amount of liquids produced. An option to do so would be using external energy sources to supply the process heat (assuming that the gaseous fraction can be converted into plastics instead of being used as fuel). This can indirectly promote the use of external energy sources such as natural gas, since this avoids using discarded plastic to fuel the process. While this keeps more material in the ‘plastics loop’, it may not be optimal from an environmental point of view since external energy supply could lead to higher climate change impacts. This issue is explored further in Paragraph 4.4.1.

3.2.2 Higher quality of recycled plastics

The quality of a recycled plastic product is influenced by the extent to which impurities (dirt, moisture) or other undesired substances (e.g. different polymer types, additives/ colourants) are removed from the input materials. Depending on the input waste plastics and the specific technical process, mechanical recycling may not be able to remove all of these materials and can degrade the material. In some cases, this limits the potential applications for recycled material. For example, most mechanically recycled plastic cannot be re-used in food contact applications (an important exception being PET bottle-to-bottle recycling). Instead, mechanically recycled plastics are used for instance in construction, car parts or textiles. The degradation occurring during mechanical recycling can limit the total number of mechanical recycling loops possible with mechanical recycling.

In contrast, chemical recycling can more easily remove/deal with undesired materials in the waste plastic inputs. For example, a gasification process can convert different polymers and additives into syngas simultaneously, which can then be used to produce new plastics.
A larger amount of off-spec polymer types is therefore not necessarily problematic for gasification. This property also means that chemical recycling can be used to upcycle some forms of plastic waste. For example, PET in fleece textile can potentially be depolymerised to produce new bottle-grade PET.

If a chemical recycling process produces intermediates that are identical to fossil fuel-based products (e.g. naphtha from pyrolysis oil), the resulting plastic is also ‘virgin-grade’. Such recycled plastics can have a higher economic value, and can potentially be re-used in demanding applications such as food packaging. Some studies have suggested using the economic value of recycled material as a correction factor for the environmental benefit of a technology. A similar reasoning could be applied when determining recycling rates, to stimulate the use of technologies that produce the highest quality outputs.

A problem for this value-based approach is the measuring point of the economic value. In general, final products with recycled material have a similar value as products made only from virgin material. Furthermore, the value of products of the same material can vary strongly over time. In general, recycling PET into PET bottles again is seen as higher value recycling than recycling to clothes, but in most cases the value of clothes per kg material is much higher than the value of PET bottles per kg.

However, the most important argument to not include the value of the materials is that the European formula used to determine recycling rates (**Equation 1**) does not take the quality of the recycled material into account. It can be noted here that also for mechanical recycling, the product quality can differ depending on how the process is run (Brouwer, et al., 2019).

Finally, it can be argued that recycled materials with a lower purity are also avoiding the use of virgin plastic production, because recycled materials are typically blended with virgin plastics in specific proportions to achieve sufficient technical properties. Nevertheless, from a scenario perspective, quality aspects are important to reach much higher recycling rates of plastic . With policies steering towards higher recycling rates, the market will also steer towards higher quality recycled material.

3.2.3 Feedstock flexibility

Some chemical recycling technologies can simultaneously process different waste types, such as combinations of different plastic types, or a combination of waste plastic with waste biomass. The current systems for collecting, sorting and recycling waste plastics are primarily based on the mechanical recycling of plastic packaging. Novel recycling technologies may not be a perfect fit for this system, as some of them can also process other waste types (non-packaging plastics, waste biomass), meaning fewer/less precise sorting of waste may be required. This could be both an environmental and an economic advantage of novel chemical recycling technologies.

The recycling rate formula is currently used to measure the recycling of plastic packaging (Equation 1), which covers about 40% of plastics used in Europe (PlasticsEurope, 2020). However, the formula could also be used to measure the recycling rate of non-packaging plastics.

The (co-)processing of waste biomass into plastics is beyond the scope of the present analysis. However, this property is relevant in more holistic analyses of the plastics production chain. For example, co-processing of biomass and plastics may make it easier to use municipal solid waste as a feedstock, preventing the need to first sort out polyolefins. Ideally, recycling systems in a circular economy would make optimal use of each technology's benefits, and ensure that 'upstream processes' such as waste sorting (and even product design) are closely aligned with recycling capacity.

3.2.4 Recycling plastics into fuels and other chemical products

Because some chemical recycling technologies break down the waste plastic into chemical building blocks, these building blocks can be used to produce a variety of products. While it is possible to recycle them into plastics, other options are also available. Most notably, pyrolysis of waste plastics can be used to produce transportation fuels. Within the Renewable Energy Directive 2 (EU, 2018), such *recycled carbon fuels* can be used by EU Member States to meet targets for renewable fuels in transportation.

Another option is to use the recycled intermediate chemicals to produce non-plastic chemical products such as cosmetics or solvents.

The current plastic packaging recycling rate calculation only includes the recycling of waste packaging to new plastic applications (Equation 1), although this does not preclude other plastic products than packaging (e.g. non-food packaging, construction, electronic equipment). However, recycling to non-plastic products such as fuels is not counted (nor to cosmetics, solvents, detergents, etc.).

3.3 Mass balance systems

The EU prescribes that in determining recycling rates a mass balance approach must be used (European Commission, 2019). The Dutch government has adopted this in the 'Regeling verslaglegging verpakkingen' and states that in case of chemical recycling the amount of recycled packaging waste will be determined using a mass balance approach. Using this approach it must become clear which part of the input into the chemical recycling process is converted into recycled plastics and which part of the input is converted into energy (Ministerie van I&W, sd). Both the EU directive and the Dutch policy document do not clarify in which cases a mass balance approach must be used and which variation of mass balancing is required (as there are several possibilities).

Below we will discuss the importance of using a mass balance approach in monitoring recycling rates. First, we explain in which cases mass balancing is relevant. This is followed by an overview of the different mass balancing approaches available and a reflection on the role of policy.

3.3.1 What is mass balancing?

Mass balancing is a bookkeeping method to keep track of recycled materials when they are blended with non-recycled materials. In addition, it can be used to allocate recycled content to specific outputs.

As mentioned in the text box in Paragraph 3.2 mass balancing is especially relevant for pyrolysis and gasification (the longer chemical recycling loops). These produce basic chemical products/intermediates that can be integrated within existing chemical industrial complexes that currently process fossil raw materials. For example, pyrolysis oil produced from recycled plastic can be mixed[14] with fossil naphtha. This mixture of recycled and virgin content can be processed in a steam cracker, producing various basic chemical products (e.g. ethylene) that are further converted into a large variety of downstream products. Physically, the recycled content is spread out over all these products.

In this situation, it is not possible or feasible to physically separate the recycled and non-recycled products. This is comparable to a power grid, where both renewable and non-renewable plants supply electricity but it is not possible to (physically) determine which kWhs are renewable. In both cases, it can be helpful to attribute the recycled/renewable to a specific output, for instance to meet government targets or for other purposes. In both cases, an accounting approach is used (since physical separation is not possible).

To keep track of recycled content in chemicals and attribute it to specific products, a transparent form of bookkeeping is required to guarantee that all sustainability claims are valid. For example, the (attributed) recycled content in the outputs should never be larger than the amount of recycled content of the inputs. This bookkeeping can be done by using a 'chain of custody' model. Several chain of custody models exist, with mass balancing being one of them. According to the chemical industry the mass balance method is most suitable in the case of using recycled content, as the recycled content is mixed with virgin content and it is not possible to differentiate between the two types of content (EMAF CE100, 2019).

3.3.2 Which variations of mass balancing exist?

Mass balancing is already applied by large chemical companies to make claims regarding recycled content of products and different organisations provide mass balance certification for these claims. However, for European policies discussions surrounding mass balancing are still ongoing, because different variations exist which have distinct benefits and downsides.

For example, the European Single Use Plastics Directive introduces mandatory requirements for minimum levels of recycled content in new plastic beverage containers. The European Commission has therefore initiated a study to evaluate, among other things, which variation of mass balancing should be applied to measure the recycled content[15]. At the time of writing, these discussions between the European Commission and various stakeholders are still ongoing.

This section aims to illustrate the difficulty in developing mass balancing systems by discussing some of the key choices that need to be made.

Firstly, any mass balance methodology needs to specify general conditions that need to be met. For example, the inputs and outputs of recycled material must be balanced over a specified time period (the recycled content allocated to products cannot exceed the amount of recycled content in the inputs). Furthermore, it has been suggested that it should not be possible to allocate recycled content to products where recycled content is not chemically or technically possible. Another consideration is whether recycled content credits can only be attributed within a chemical production site, or whether the credits can be transferred/aggregated across different sites. This last option (multi-site transfers) could

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[14] Note that it is not required to actively blend these streams. The pyrolysis-derived oil can be fed into a chemical production network on the same locations as fossil naphtha so that they mix naturally.

[15] See e.g. https://www.eunomia.co.uk/eunomia-to-explore-options-for-measuring-recycled-content-across-europe/

make small-scale chemical recycling installations more economically viable (Eunomia, 2021), but would further increase the gap between where the recycled content is physically processed and where it is attributed.
Secondly, different physical properties can be measured to determine recycled content in the inputs and outputs (EMAF CE100, 2019).

- **Mass**: The recycled content and virgin content in the input is simply weighed and the recycled content is allocated based on the weight. This method is suitable when the composition of the fossil and the recycled feedstock are similar.
- **Carbon**: The share of recycled content in the feedstock mixture and the output is determined by counting the carbon atoms in both the recycled feedstock and the virgin feedstock. This method is most suitable when the recycled and virgin feedstock have different compositions and only the to be recycled fraction must be tracked.
- **Lower heating value**: The lower heating value represents the energy content of a material. With this method the lower heating value of both the virgin and the recycled feedstock is determined to allocate the recycled content to output products. This method should be used when the input materials have a large variation in composition.

Lastly, different rules can be set up to specify among which outputs the recycled content can be allocated. This is often illustrated using the example of a steam cracker fed by a mix of recycled and fossil inputs. These inputs are transformed into process losses, products directly linked to polymer production, other material outputs and fuel outputs. Four variations of mass balancing can be distinguished (with more variations possible):

1. **Technical balance**: Recycled content can only be allocated on the basis of what is theoretically present in the output product. All products receive a proportional share of the recycled content in the inputs.
2. **Polymers only**: Only the recycled content present in outputs directly linked to the production of polymers can be freely allocated.
3. **Fuels exempt**: Recycled content in all outputs except fuels and process losses can be freely allocated.
4. **Free allocation**: Recycled content in all outputs except process losses can be allocated freely.

Note that in all the variations presented here, it is not allowed to allocate the recycled content in process losses to other outputs. Material that is lost in the process cannot be viewed as recycled material.

3.3.3 How can mass balancing policy affect novel recycling routes?

At the moment there is no clear government policy on what variant of mass balancing the industry should use. In practice, it seems that most companies currently use a combination of ‘free allocation’ and/or ‘fuels exempt’. The recycled content in losses and fuels that are used onsite as energy source is not allocated to products. However, upcoming decisions by policymakers on the ‘rules’ surrounding mass balancing for future policies (such as the Single Use Plastics Directive mentioned above) will determine how mass balancing can be applied in specific cases. In turn, this can affect the economic viability of specific plastic recycling routes.

From an industrial perspective, the mass balancing variations that provide more freedom (such as ‘free allocation’) are attractive. If there are few limitations, the recycled content can be attributed to those end-products where consumer demand for recycled content is high or where there are other policy incentives (e.g. mandatory recycled content levels). This can make specific recycling routes economically viable – for example, in a process which produces a wide range of outputs which are only partly destined for polymer production, recycled content could be attributed to the polymer products if consumer demand for recycled plastics is high. By improving the business cases for chemical recycling projects, the development of the technologies could be sped up as more projects are implemented. In contrast, more restrictive mass balancing rules can have the opposite effects. If the 'technical balance' model is adopted for instance, recycled content will be attributed to products where there is no market value for recycled products. According to Eunomia, it is the position of the European chemical industry association Cefic that 'free allocation' mass balancing should be adopted for all recycled content targets (Eunomia, 2021).

However, some NGOs are critical on mass balancing. They have for instance argued that providing a large amount of freedom in mass balancing can lead to greenwashing and can be misleading to consumers (Zero Waste Europe, 2021). In the 'free allocation' approach, the recycled content that physically ends up in a fuel can be attributed to a plastic product. A consumer could be purchasing a bottle 'made from recycled content' to contribute to a circular economy, while the physical recycled content is combusted as a fuel. This issue could be mitigated to some extent by setting and enforcing clear rules on which kind of product claims are allowed when mass balancing has been used. Nevertheless, 'free allocation' can create a fundamental mismatch between how much recycled content is physically stored in products in the economy and how much has been attributed.
To illustrate: it is possible to make all plastics in the economy fully recycled with 'free allocation' (by attributing recycled content from fuels to polymers), but you would still need to feed-in crude oil to produce them.

In our view, the 'fuels exempt' variation represents an appropriate compromise between very strict and very lenient rules. The plastic-to-plastic yields derived using 'fuels exempt' mass balancing correlate with the carbon footprints of the technologies (see details in Paragraph 4.4.2). It enables companies to attribute recycled content to specific products that meet specific policy goals or that are economically attractive. This helps to make chemical recycling more viable and can enable a faster rollout of technologies that can convert difficult plastic waste streams to new products and reduce climate change impacts. At the same time, 'fuels exempt' does not enable companies to attribute recycled content from fuels to polymers. This means that recycled content that is physically removed from the economy (i.e. combusted as a fuel) cannot be attributed to plastic products. This stimulates companies to develop technologies that produce as much plastic (precursor) outputs as possible and to increase plastic yields as much as possible.

A downside of 'fuels exempt' compared to 'free allocation' is that by providing less freedom to companies in attributing recycled content, the economic viability of some projects could be affected. This could lead to more limited/slower uptake of novel recycling technologies. Regardless of the mass balancing method implemented, recycled content claims that are derived from mass balancing should be clearly indicated to avoid misleading consumers.

4 Plastic-to-plastic yields of chemical recycling

4.1 Goal and approach

The primary goal of this chapter is to operationalise the plastic-to-plastic yield indicator and to apply it to different waste plastic treatment routes using company-supplied data (incineration, mechanical recycling, pyrolysis, gasification, depolymerisation and solvent-based extraction).

It should be noted that the analysis aims to determine the amount of plastic material conserved by different recycling options. The goal is therefore not to determine how sustainable different processes are or how much fossil material production is avoided.

CE Delft shared a questionnaire (see Annex B) and organised follow-up discussions with ten industrial parties to estimate the plastic-to-plastic yield of different recycling routes.
In addition to gathering these yields, specific attention has been paid to understanding the uncertainties, limitations and/or conditions surrounding these yields.

In some cases, companies could not provide all the required information, for instance because they are only involved in part of the production chain. In these cases (shown in Table 7 in Annex A) the values they provided have been supplemented with data from other (public) sources.

In addition, because some chemical recycling technologies may have a higher energy than mechanical recycling, we gathered information on the energy input/output of the different technologies. An additional analysis in which an additional indicator is developed which also accounts for the energy use of processes is presented in Paragraph 4.4.1. Finally, to put all yields and comparisons of technologies in perspective, we analyse in Paragraph 4.4.2 whether the yields derived here correlate with carbon footprint results.

4.2 Operationalisation of the plastic-to-plastic yield

This section operationalises a plastic-to-plastic yield indicator for chemical recycling.
The purpose of the plastic-to-plastic yield is to show to what extent specific (chemical) recycling technologies for plastics contribute to national recycling targets. The plastic-to-plastic yield defined here is applied to a range of waste plastic treatment technologies in Chapter 4.

As discussed in Paragraph 3.1, the same system currently used for mechanical recycling can also be used for chemical recycling of plastics. The same measurement point and calculation point can be used, although (some forms of) chemical recycling can have substantially more processing steps in between these points.

For this report, we define the plastic-to-plastic yield of a recycling technology as the amount of new plastic (by weight) that can be produced from 1 tonne of plastic in plastic waste sent to recycling (Equation 2).

Equation 2

$$Plastic - to - plastic\ yield\ (\%) = \frac{Recycled\ plastic\ entering\ compounding\ (by\ weight)}{Plastic\ sent\ to\ recycling\ (by\ weight)}$$

The plastic-to-plastic yield is the amount of recycled plastic at the *calculation point* that is produced from 1 tonne of waste plastic sent to recycling at the *measuring point (*see e.g. Figure 10). The calculation point is defined in line with EU regulation on measuring plastic packaging recycling rates, in which all recycled material entering compounding count towards the targets (Brouwer, et al., 2019). At the measuring point, only the plastic material entering a recycling process is measured; the weight of other materials (e.g. biomass, dirt, moisture) is not counted.

By comparing the weight of plastics entering a recycling process and the weight of plastics entering compounding, the yield accounts for any plastic losses that occur during recycling and subsequent processes (for example when processing recycled basic chemical building blocks into recycled polymers).

There are some key aspects of the plastic-to-plastic yield that should be noted:
- A plastic-to-plastic yield corresponds to a particular recycling technology (or chain of technologies) operating in specific conditions. The yield can for instance depend on the plastic feedstock used, operating conditions and downstream processing choices. For example, the plastic-to-plastic yield of a pyrolysis-based recycling chain aiming to replace fossil naphtha and to produce recycled plastics will differ from the plastic-to-plastic yield of a pyrolysis-based recycling chain aiming to replace fossil diesel. When discussing plastic-to-plastic yields, it is therefore important to always note its key characteristics, i.e. the technology, feedstock mix, output products, whether mass balancing is used, and other remarks if applicable.
- Only the amount of *recycled* material entering compounding is counted in the yield. This is relevant to reiterate since recycled basic chemicals may be combined with virgin or fossil chemicals during polymer production. For example, recycled ethylene may be reacted with oxygen and fossil terephthalic acid to produce (partially recycled) PET. In this case, only the recycled fraction is counted.
- The composition of the waste plastic sent to a recycling process, i.e. the amount of plastic, biomass, dirt, moisture or other materials, can vary greatly between sorting processes, recycling processes, and over time. Because the current analysis focusses only on the plastic share in this input, the influence of such differences is reduced. Nevertheless, the measurement point should be kept constant to ensure fair comparisons across technologies.
- Because the calculation point is placed at plastic compounding, any conversion of feedstock into fuels or non-plastic products is not counted. When applicable however, mass balancing is allowed to allocate recycled content to specific outputs such as plastics. Mass balancing can lower the barriers for plastic recycling, as recycled material can gradually be fed into existing chemical infrastructure. Nevertheless, it is important to ensure that all conditions for mass balancing are met (e.g. avoiding double counting) and that the rules used are harmonised.
- The energy use of chemical recycling technologies should be studied further. Because the plastic-to-plastic yield proposed here focusses on the output of recycled plastics only, technology developers could be incentivised to minimise material losses even if this increases environmental impacts (discussed in Paragaph 3.2.1). This topic is addressed further in Paragraph 4.4.1.

- Since the purpose is to measure the recycling of discarded plastics, the conversion of biomass, paper or other carbon-containing material to plastics is not included in the yield.
- No correction for the quality or economic value of the quality of the produced outputs has been applied. This means the plastic-to-plastic yields aligns with the current approach for mechanical recycling.
- Novel chemical recycling technologies offer other potential benefits such as feedstock flexibility or the potential to recycle plastics into different product categories. These should be considered in the overall design of collection, sorting and recycling systems, but do not directly relate to the plastic-to-plastic yield and are therefore not taken into account here.

4.3 Results: plastic-to-plastic yields

Based on the questionnaires returned by industry and subsequent discussions with companies, CE Delft prepared an overview of the plastic-to-plastic yield estimates for different processes. In addition to data gathered for chemical recycling, literature was used to calculate plastic-to-plastic yields for different forms of mechanical recycling and incineration with energy recovery (based on the Dutch situation). The full overview per technology is shown in Annex A (including information on the use of literature or assumptions).

Table 3 provides an overview of plastic-to-plastic yields that could be used to monitor the contribution of different technologies to the national recycling targets. The table includes conservative values taken from Annex A.

Some remarks related to the values listed should be highlighted here:
- The results provide a first indication of the expected plastic-to-plastic yields and show how specific companies currently expect their technologies to perform.
- The plastic-to-plastic yields do not (necessarily) indicate how much fossil plastic is displaced when implementing the technology. For example, depending on the application of mechanically recycled mixed plastic waste, not just plastics but also wood or concrete may be replaced.
- The studied technologies can be operated and combined in different ways and may be optimised for different goals. For example, some pyrolysis developers target plastics as feedstock, while others aim to process a combination of plastics and biomass. Furthermore, some may aim to produce fuels, some may target the substitution of virgin naphtha, and some may combine pyrolysis with a downstream treatment step to produce specific chemical intermediates. These factors can all affect the overall plastic-to-plastic yield, and could offer other benefits and/or downsides as well[16]. In the present study, there is insufficient data available to distinguish between variants of the technologies. For pyrolysis, this means a ‘standard production chain’ has been studied, i.e. the processing of feedstock consisting mostly of polyolefin plastic in pyrolysis into PE plastics.
- Furthermore, for pyrolysis we assume the outputs of recycled intermediate chemicals are fed into existing chemical infrastructure and blended with virgin inputs. In these cases, a mass balance approach may have been used to allocate recycled content to specific outputs of the chemical complex (i.e. plastics or intermediates bound for plastic production). See also Paragraph 3.3.

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[16] For example, co-processing of biomass and plastics may make it easier to use municipal solid waste as a feedstock, preventing the need to first sort out polyolefins.

Table 3 - Default plastic-to-plastic yields for specific recycling routes

Technology	Number of respondents/ sources	Plastic/ feedstock type	Plastic-to-plastic yield	Remarks
Incineration with energy recovery	1	Any plastic	0%	
Mechanical recycling	2	LDPE/foils	78-97%	(Brouwer, et al., 2018) (CE Delft, 2021) Based on estimations and subject to uncertainties
	2	PP	94-100%	
	2	PET	95-100%	
	2	HDPE	95-100%	
	2	Mixed plastic waste	56-83%	
Solvent-based extraction	1	PS	100%	
Depolymerisation	2	PET	97%	
Pyrolysis	6	PE/PP/Mixed plastic waste/Foils	49%	Losses can occur during further sorting, pyrolysis itself and steam cracking. Plastic-to-plastic yield is valid when pyrolysis and downstream processes target plastic production (not fuel) and when mass balancing is applied to allocate recycled content to plastics.
Gasification	2	Mixed plastic waste	34%[a]	Plastic-to-plastic yield for conversion to polyolefins (PE or PP). Losses occur during gasification and conversion to final products. Yields correspond to situation where hydrogen is added during the process. Assumed a methanol to olefin conversion yield of 44% (based on chemical reaction). No losses during polymerisation assumed.

a) Uncertain value for route to polyolefins, see ‘Data accuracy’ in Paragraph 1.5.

4.4 Discussion

4.4.1 Evaluating energy use of different waste treatment options

In this section, we explore a second plastic-to-plastic yield, which also takes into account the energy consumption of different processes. To do so, company information on the overall energy consumption of the recycling chain is used. To express material and energy inputs in the same units, the cumulative energy demand[17] is used (see details below).

This second plastic-to-plastic yield (corrected for material and energy inputs) is a first attempt to put the material losses of different technologies into context. For example, during pyrolysis a part of the feedstock is used to fuel the process, which results in a

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[17] The cumulative energy demand (CED), expressed in MJ, corresponds to the total life cycle primary energy required to produce a product or energy carrier. For electricity for example, the cumulative energy demand calculates how much energy needs to be extracted from nature to produce 1 kWh. This metric accounts for the share of different sources of electricity (e.g. coal, natural gas, wind), and covers all conversion losses and processing steps that occur from the extraction of primary energy from nature to the delivery of 1 kWh.

relatively low plastic-to-plastic yield (Table 3). However, other plastic waste treatments can require *external* sources of energy, which also (typically) requires fossil energy sources. By including both the energy and materials consumption in a single indicator, we can get a better idea of the overall impact of a waste treatment process on the environment[18]. Nevertheless, it is not trivial to derive an appropriate indicator as different implementations are possible (see also the remarks below Table 5 -).

For this analysis, a second plastic-to-plastic yield based on both energy and materials is defined as shown in Equation 3.

Equation 3

$$\frac{Recycled\ plastic\ entering\ compounding\ (as\ CED) + Energy\ outputs\ (as\ CED)}{Plastic\ sent\ to\ recycling\ (as\ CED) + Energy\ inputs\ (as\ CED)}$$

The following methodological remarks apply:

- Respondents were asked to report the amount of external energy sources (e.g. electricity, heat, hydrogen, …) needed for the different process steps.
- In some cases, the energy use of the polymerisation step was not given by the questionnaire respondents. Here, CED values from the Eco-profiles of PlasticsEurope have been used (5.85 MJ CED/kg HDPE and 5.7 MJ CED/kg PET).
- To determine the CED of the feedstock (plastic sent to recycling), plastic output and energy inputs/outputs, the values shown in Table 4 are used.
- In the case of electricity, the average electricity mix is used, as this study attempts to provide plastic-to-plastic yields indicative for the technologies in general.
- It is assumed that none of the studied processes, excluding incineration with energy recovery, produce energy which can be sold/exported. Energy outputs are included in Equation 3 to also include incineration with energy recovery in this overview.

Table 4 - Cumulative energy demands of materials and energy

Material or energy	Unit	Cumulative energy demand
Electricity (Dutch mix)	1 kWh	9.3 MJ
Natural gas	1 m^3	46.9 MJ
Steam	1 kg	4.6 MJ
Heat	1 MJ	0.5 MJ
HDPE (represents all plastics)	1 kg	77 MJ

Table 5 - compares the results of both the plastic-to-plastic yield indicators.

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[18] While this indicator may provide a better indication of the overall environmental impact of a plastic waste treatment, a full life cycle assessment (LCA) study is required to account for all inputs and outputs and their environmental impact. For example, the indicator developed here does not account for the use of auxiliary materials during a recycling process and does not account for the quality of the produced outputs. Such factors could be taken into account in a full LCA.

Table 5 - Comparison of plastic-to-plastic yields based on 1) material inputs only, and on 2) both material and energy inputs

Technology	Plastic/feed stock type	Plastic-to-plastic yield		Remarks
		1. Material inputs only (Table 3)	2. Material and energy inputs	
Incineration with energy recovery	Any plastic	0%	16-29%	Yield 2 depends on the LHV of the plastic incinerated and the chosen MSWI.
Mechanical recycling	LDPE/foils	78-97%	66-82%	
	PP	94-100%	85-89%	
	PET	95-100%	91-96%	
	HDPE	95-100%	81-90%	
	Mixed plastic waste	56-83%	49-73%	
Solvent-based extraction	PS	100%	66% (conservative value)	Electrified process, resulting in high CED for energy input.
Depolymerisation	PET	97%	75%	
Pyrolysis	PE/PP/ Mixed plastics/ Foils	46%	44%	
Gasification	Mixed plastics	34%	-	Insufficient information available to calculate yield based on material and energy inputs.

Some preliminary conclusions from this analysis are:

- Except for foils and mixed plastic waste, the analysed data for mechanical recycling shows a (material and energy-based) yield between 85 and 93%. This 85% could be viewed as a benchmark typical for mechanical recycling.
- For mixed plastics and foils, which are more difficult to recycle, we find a (material and energy-based) yield of 52 to 79%.
- For depolymerisation, a (material and energy-based) yield of 75% is derived, which is only slightly worse than the best mechanical recycling, but better than foils and mixed plastic recycling (75%/84% = 0.9).
- Pyrolysis has a (material and energy-based) yield of 44%, which is very similar to the material yield because the process’ energy requirement is provided from the feedstock. This yield is close to half of the better mechanical recycling processes (44%/84% = 0,52).
- Solvent-based PS recycling has a very high mass yield but the energy demand makes the (material and energy-based) yield considerably lower. This is likely due to the specific set-up of this company (further discussed below).

Some important limitations/remarks should be mentioned regarding these results:

- The plastic-to-plastic yields for the materials-only indicator for mechanical recycling are derived from information from Wageningen University (Brouwer, et al., 2018). This study does not indicate the amount of energy used in the recycling process. For the plastic-to-plastic yields based on material and energy, we therefore combined our own data on energy use for mechanical recycling with the material based yields from Wageningen University (CE Delft, 2021).

- In this study we want to determine plastic-to-plastic yields applicable to chemical recycling technologies in general. The yields based on material input only do not show a large variation between different companies. The energy inputs, on the other hand, seem much more site-specific, as there are large differences in the energy inputs reported by the companies. In Table 5 we have chosen to report conservative values (in line with the values in Table 3). For depolymerisation, for example, the most optimistic (material and energy-based) yield was 87%. For pyrolysis the most optimistic (material and energy-based) yield is 58%, which corresponds to a (material-based) yield of 58% as well.
- Furthermore, not all companies reported the energy inputs in their process, or not for the whole process. Therefore, the yields corrected for energy inputs are not based on the same amount of data points as the yields for material input only.
- Expressing the material and energy input and output in cumulative energy demand results in a lower yield for companies using large amounts of electricity, as the cumulative energy demand of electricity is relatively high. This disadvantages companies that have largely electrified their processes for sustainability reasons. This is the case, for example, with solvent-based extraction. The yield is based on the information of one company, which has entirely electrified its process. However, according to the company the energy is mostly used for heating purposes. This energy could also be supplied by natural gas, for example, which would result in a lower cumulative energy demand of the energy input and a higher (material and energy-based) yield).

4.4.2 Correlation with carbon footprint results

This section investigates to what extent the plastic-to-plastic yields derived here correlate to carbon footprint results from prior research. Table 6 shows indicative carbon footprint results for the various technologies previously derived by CE Delft (2019). Note that these are expressed as reductions compared to incineration of the same materials in a municipal solid waste incinerator (MSWI). The table also shows the plastic-to-plastic yields from Table 3.

Overall, the highest carbon footprint reductions are achieved by mechanical recycling of mono-material streams and solvent-based purification/depolymerisation. These also have the highest plastic-to-plastic yields (an exception being mechanical recycling of LDPE foils). These technologies are followed by mechanical recycling of mixed plastic (reduction of 2 kg CO_2 eq./kg waste input), which has a substantially lower plastic-to-plastic yield as well. Finally, pyrolysis/gasification result in the lowest carbon footprint reductions and also have the lowest plastic-to-plastic yields.

We therefore observe the same trend for both these indicators. This is unsurprising, since higher product yields will generally yield better carbon footprint outcomes as well. Nevertheless, this is a very preliminary analysis, since the carbon footprint and plastic yield results are derived based on different underlying data and may correspond with different feedstock compositions, technologies, etc.

Table 6 - Carbon footprint reductions of recycling technologies compared to incineration with energy recovery. Adapted from CE Delft (2019)

Technology	**Carbon footprint reduction compared to incineration in MSWI** kg CO_2 eq./kg plastic in waste [A]	**Plastic-to-plastic yields** (Table 3) [B]	**[B] / [A] * 100**
Mechanical recycling mono-materials	2.5 to 3.5	89-100%	25-36
Mechanical recycling mixed plastic	Around 2	60%	30
Solvent-based purification/ depolymerisation	Around 3	97-100%	32-33
Pyrolysis	Around 1.5	49%	33
Gasification	1.0 to 1.5	34%	23-34

To check whether there is a correlation between the estimated CO_2 reductions and the plastic-to-plastic yields, we divided both numbers on the column on the far right.
The resulting numbers can (only) be used to check this correlation. For chemical recycling, the results vary between 23 and 34. The difference with the range for mechanical recycling (25-36) is small. This suggests that the presented plastic-to-plastic yields correlate with the CO_2 reduction figures of the technologies.

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A Plastic-to-plastic yield data

A.1 Data overview

CE Delft shared a questionnaire and organised follow-up discussions with ten industrial parties to estimate the plastic-to-plastic yield of different recycling routes.
The questionnaire is shown in Annex B.

Table 7 provides an overview of the data gathered on the plastic-to-plastic yields of waste plastic treatment options. Note that the data for solvent-based extraction, depolymerisation and pyrolysis has been gathered specifically for this analysis, whereas the information for incineration and mechanical recycling is taken from prior research.

Table 7 - Data on plastic-to-plastic yields (see definition in Paragraph 4.1) of waste plastic treatments

Technology / feedstock	Plastic in input (kg/tonne input)	Plastic yield (kg/tonne input)	Plastic-to-plastic yield	Feedstock quality	Remarks
Incineration with energy recovery					
Incineration with energy recovery	1,000	0	0%		All types of plastic.
Mechanical recycling (source separation)					
LDPE/foil			78-97%	DKR 310	(Brouwer, et al., 2018) (CE Delft, 2021) Based on estimations. Note that the yield for mixed plastic waste corresponds to mechanical recycling to mixed plastic products such as outdoor furniture.
PP			94-98%	DKR 324	
PET			97-99%	DKR 328	
HDPE			95-98%	DKR 329	
Mixed plastic waste (MPW)			56-83%	DKR 350	
Mechanical recycling (post-separation)					
LDPE/foil			78-89%	DKR 310	(Brouwer, et al., 2018) (CE Delft, 2021) Based on estimations. Note that the yield for mixed plastic waste corresponds to mechanical recycling to mixed plastic products such as outdoor furniture.
PP			99-100%	DKR 324	
PET			95-100%	DKR 328	
HDPE			99-100%	DKR 329	
Mixed plastic waste (MPW)			63-83%	DKR 350	
Solvent-based extraction					
Company 1 - PS	900	900	100%	Feedstock also contains metal, cement residue and bitumen residue	
Depolymerisation					
Company 2 - PET bottles	991	982	99%	Bottle flakes, DKR 328-1	
Company 2 - PET trays	916	886	97%	Non-PET input is mostly colours	
Company 2 - PET textile	970	952	98%	PET textile with 3% cotton	
Company 3	1,000	1,000	100%	DKR 328-1	

Technology / feedstock	Plastic in input (kg/tonne input)	Plastic yield (kg/tonne input)	Plastic-to-plastic yield	Feedstock quality	Remarks
Pyrolysis					
Company 4	1,000	495	50%	Mixed plastic waste, 10% plastic with low heating value is lost in pre-treatment	
Company 5	848	435	51%	DKR 310 with 84,8% useful material. 15% of the useful material is lost in pre-treatment.	
Company 6	980	570	58%	DKR 350 and DKR 352 with high polyolefin content (>90%)	Only information on the plastic-to-pyrolysis oil yield provided. Pyrolysis oil-to-plastic yield is based on information from company 4.
Company 7	900	391	43-58%	DKR 350 and DKR 310, ~70% polyolefins, ~20% PET	Process produces two main product streams. One fraction (aromatics) can directly be used in existing chemical industry; further potential losses (purification/ polymerisation) are not included. The other fraction is a naphtha-like oil, which can be used as a fuel or converted into plastics. The lower end of the plastic-to-plastic yield (43%) corresponds to fuel use of the oil fraction. The higher end (58%) corresponds to situation in which this fraction is used in crackers to produce polyolefins, assuming average losses (Table 8).
Company 8	975	584	60%	DKR 350 and DKR 310 with mostly PE (94%)	Only information on the plastic-to-pyrolysis oil yield provided. Pyrolysis oil-to-plastic yield is based on information from company 4.
Gasification					
Company 9	240	96	40%	Dry matter (80%) consists of 30% biomass and 60% plastics	Feedstock contains both plastic and biomass. Assumption that both contribute evenly to methanol production. Only valid when hydrogen is added during gasification process.
Company 10	930	317	34%	Hard to recycle mixed plastic waste with varying polymer types (mostly polyolefins)	
Uncategorised technology					
Company 11	590	289	49%	50-70% plastic on ash- and water-free basis (and 30-50% biomass)	Feedstock processes both plastic and biomass. Polymerisation losses not included.

As partly already mentioned in the main text in Paragraph 4.3, a number of remarks related to the findings in Table 7 should be highlighted here:

- The results provide a first indication of the expected plastic-to-plastic yields and show how specific companies (expect to) perform.
- The results are not intended to benchmark companies among each other.
- The plastic-to-plastic yields shown do not (necessarily) indicate how much fossil plastic is replaced. For example, depending on the application of mechanically recycled mixed plastic waste, not just plastics but also wood or concrete may be replaced.
- The studied technologies can be operated and combined in different ways and may be optimised for different goals. For example, some pyrolysis developers target plastics as feedstock, while others aim to process a combination of plastics and biomass. Furthermore, some may aim to produce fuels, some may target the substitution of virgin naphtha, and some may combine pyrolysis with a downstream treatment step to produce specific chemical intermediates. These factors can all affect the overall plastic-to-plastic yield, and could offer other benefits and/or downsides as well[19]. In the present study, there is insufficient data available to distinguish between variants of the technologies. For pyrolysis, this means a 'standard production chain' has been studied, i.e. the processing of feedstock consisting mostly of polyolefin plastic in pyrolysis into PE plastics.
- Furthermore, for pyrolysis we assume the outputs of recycled intermediate chemicals are fed into existing chemical infrastructure and blended with virgin inputs. A Mass Balance approach can be used to allocate recycled content to specific outputs of the chemical complex (i.e. plastics or intermediates bound for plastic production). This approach is in line with ISCC PLUS mass balance certification ('free attribution'), and we assume the same conditions are met that should be met for ISCC PLUS mass balancing (i.e. it must be chemically possible that the atoms are included in the attributed output).
- It is possible that in some cases the 'plastic sent to compounder' in the yield formula also contains non-plastic materials. For example, sand or other impurities may be present in the plastic sent to compounding extruders and may therefore be weighed and counted as 'recycled plastic'. This could mean that the plastic-to-plastic yields for mechanical recycling in particular are overestimated, although the effect is likely small.

A.2 Pyrolysis: losses per sub-process

The novel recycling options for plastic waste that are considered here typically consist of various sub-processes. To understand where material losses occur, the questionnaire included the option to specify losses per sub-process.

This information is especially interesting for pyrolysis, for which we derived a comparatively low plastic-to-plastic yield but obtained information from a comparatively large amount of companies (Table 7). Three companies provided sufficient information to break down the overall yield into sub-processes, indicated in Table 8. This shows that most losses occur during pyrolysis itself and during steam cracking. In these steps, a part of the feedstock material is converted into gases that are used to fuel the pyrolysis/cracking processes.

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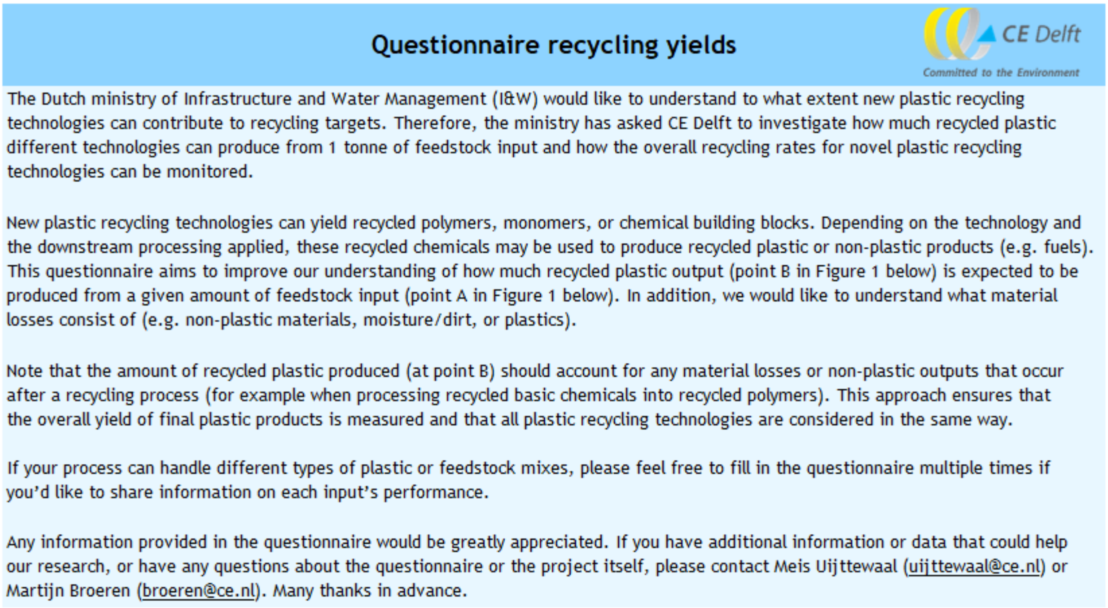
[19] For example, co-processing of biomass and plastics may make it easier to use municipal solid waste as a feedstock, preventing the need to first sort out polyolefins.

Table 8 - Typical plastic losses in pyrolysis sub-processes (from 3 company sources). Note that all losses are dependent on the composition of the feedstock used.

Pre-treatment	Pyrolysis	Purification/hydrogenation	Cracking	Polymerisation
10-15%	25-30%	2%	17-20%	1%

B Questionnaire recycling yields



Questionnaire recycling yields

The Dutch ministry of Infrastructure and Water Management (I&W) would like to understand to what extent new plastic recycling technologies can contribute to recycling targets. Therefore, the ministry has asked CE Delft to investigate how much recycled plastic different technologies can produce from 1 tonne of feedstock input and how the overall recycling rates for novel plastic recycling technologies can be monitored.

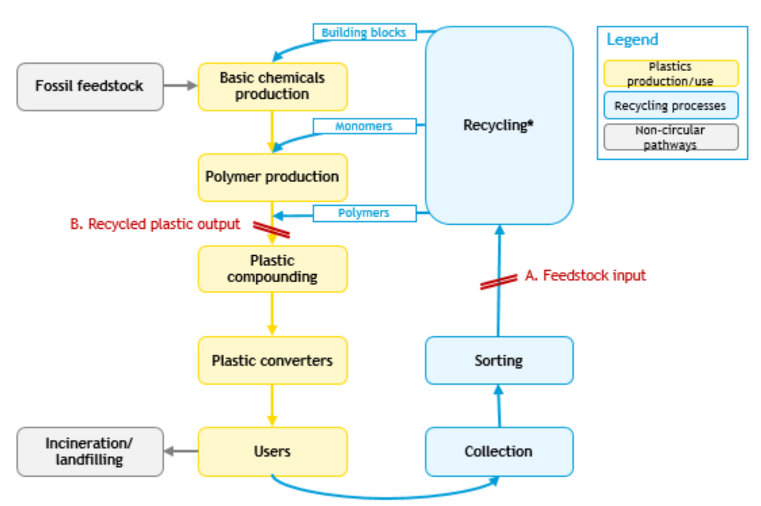
New plastic recycling technologies can yield recycled polymers, monomers, or chemical building blocks. Depending on the technology and the downstream processing applied, these recycled chemicals may be used to produce recycled plastic or non-plastic products (e.g. fuels). This questionnaire aims to improve our understanding of how much recycled plastic output (point B in Figure 1 below) is expected to be produced from a given amount of feedstock input (point A in Figure 1 below). In addition, we would like to understand what material losses consist of (e.g. non-plastic materials, moisture/dirt, or plastics).

Note that the amount of recycled plastic produced (at point B) should account for any material losses or non-plastic outputs that occur after a recycling process (for example when processing recycled basic chemicals into recycled polymers). This approach ensures that the overall yield of final plastic products is measured and that all plastic recycling technologies are considered in the same way.

If your process can handle different types of plastic or feedstock mixes, please feel free to fill in the questionnaire multiple times if you'd like to share information on each input's performance.

Any information provided in the questionnaire would be greatly appreciated. If you have additional information or data that could help our research, or have any questions about the questionnaire or the project itself, please contact Meis Uijttewaal (uijttewaal@ce.nl) or Martijn Broeren (broeren@ce.nl). Many thanks in advance.

Figure 1 - Schematic overview of (chemical) plastic recycling processes



* In this model, **recycling** includes all steps required to convert the input (sorted plastics) to a product ready to be used in the existing plastic production chain, i.e. to substitute fossil chemicals/polymers. All pre-treatment steps, mechanical and/or chemical recycling itself, and final purification or upgrading steps are included.

1. Overall recycling system

1a. **Which plastic feedstock do you (expect to) use for your recycling technology? If a material meeting a DKR specification is used, please indicate the type (e.g. DKR328).**

1b. **Where is the plastic feedstock sourced? Is the material produced in existing sorting installations (e.g. DKR streams), or is it sourced elsewhere?**

1c. **What is the (expected) material composition of this feedstock by weight?**

Plastics		%		
PET		%		
PE		%		
PP		%		
PS		%		
PVC		%		
PU		%		
Other		%	Namely:	
Biomass		%		
Paper		%		
Metal		%		
Glass		%		
Moisture		%		
Other		%	Namely:	

1d. **When 1000 kg of this feedstock (defined in question 1c) enters the recycling system (point A in figure 1), what is the (expected) amount of recycled plastic produced (point B in figure 1)?**

kg

Please account for any (expected) losses between point A and point B in the figure above. Losses could for instance occur when dirt/moisture or offspec polymer types are removed, when fuel gas produced from plastic waste is used internally, or when non-plastic products such as fuels are produced.

Note: if it is not possible to estimate all losses at once, please indicate expected losses per individual process in Section 2 of the questionnaire.

1e. **Is the recycled plastic output (defined in question 1d) produced only from waste plastics, or also from biomass present in the feedstock mix?**

Recycled plastic produced from waste plastic		kg
Recycled plastic produced from biomass		kg

1f. **Which outputs are produced from the feedstock in addition to recycled plastic? Consider e.g. non-plastic products, but also wastes and emissions.**

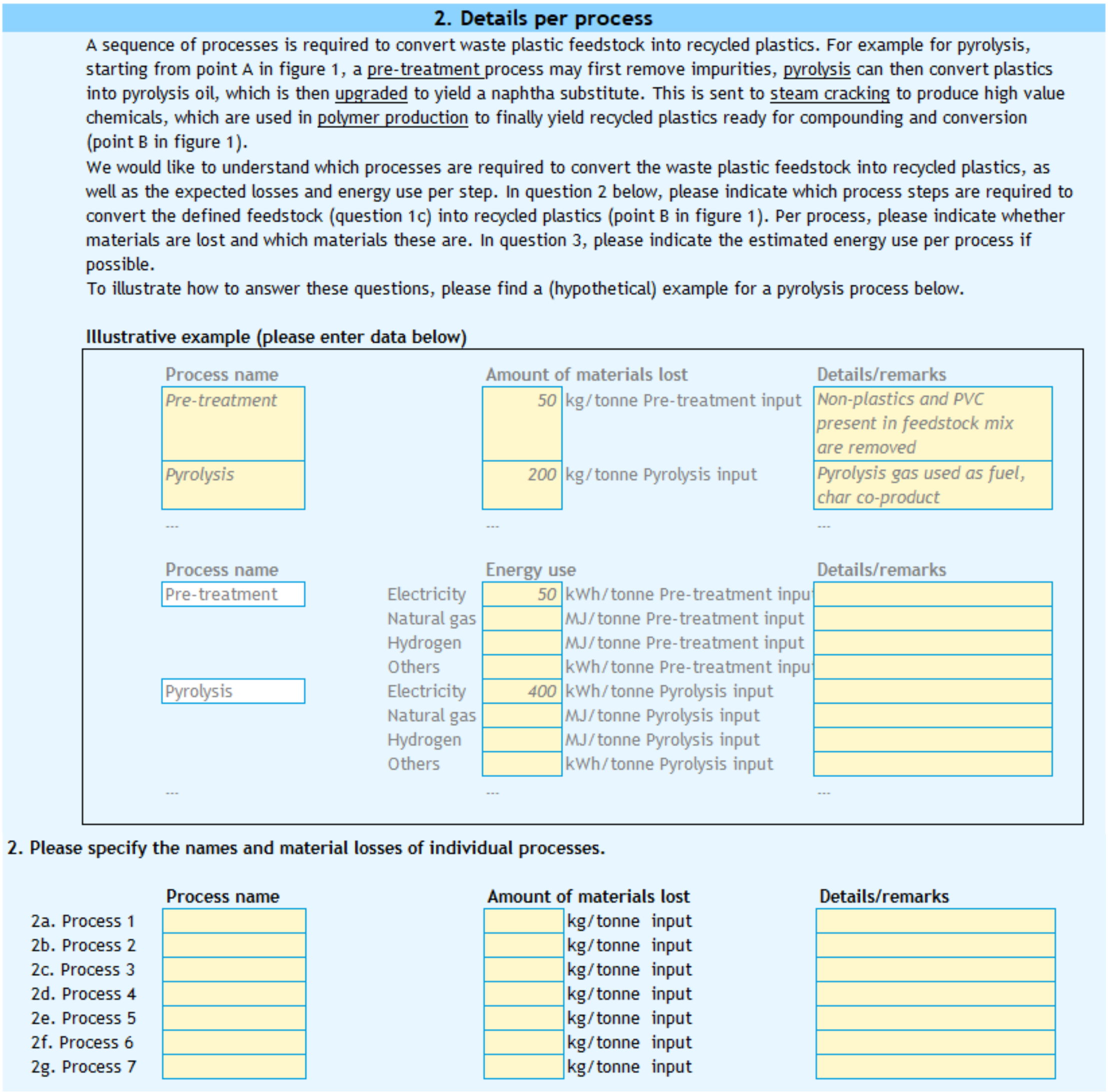
1g. **In case recycled and fossil feedstocks are mixed/blended somewhere in the production chain: Is a Mass Balance approach used to allocate recycled content to specific products?**

If so:

> Is all recycled content allocated to plastic outputs?

> Is the allocation based on mass, energy content or carbon content?

> What would be the answer to question 1d if no Mass Balance method were used?



2. Details per process

A sequence of processes is required to convert waste plastic feedstock into recycled plastics. For example for pyrolysis, starting from point A in figure 1, a pre-treatment process may first remove impurities, pyrolysis can then convert plastics into pyrolysis oil, which is then upgraded to yield a naphtha substitute. This is sent to steam cracking to produce high value chemicals, which are used in polymer production to finally yield recycled plastics ready for compounding and conversion (point B in figure 1).

We would like to understand which processes are required to convert the waste plastic feedstock into recycled plastics, as well as the expected losses and energy use per step. In question 2 below, please indicate which process steps are required to convert the defined feedstock (question 1c) into recycled plastics (point B in figure 1). Per process, please indicate whether materials are lost and which materials these are. In question 3, please indicate the estimated energy use per process if possible.

To illustrate how to answer these questions, please find a (hypothetical) example for a pyrolysis process below.

Illustrative example (please enter data below)

Process name	Amount of materials lost		Details/remarks
Pre-treatment	*50*	kg/tonne Pre-treatment input	*Non-plastics and PVC present in feedstock mix are removed*
Pyrolysis	*200*	kg/tonne Pyrolysis input	*Pyrolysis gas used as fuel, char co-product*
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Process name		Energy use		Details/remarks
Pre-treatment	Electricity	*50*	kWh/tonne Pre-treatment inpu	
	Natural gas		MJ/tonne Pre-treatment input	
	Hydrogen		MJ/tonne Pre-treatment input	
	Others		kWh/tonne Pre-treatment inpu	
Pyrolysis	Electricity	*400*	kWh/tonne Pyrolysis input	
	Natural gas		MJ/tonne Pyrolysis input	
	Hydrogen		MJ/tonne Pyrolysis input	
	Others		kWh/tonne Pyrolysis input	
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2. Please specify the names and material losses of individual processes.

	Process name	Amount of materials lost		Details/remarks
2a. Process 1			kg/tonne input	
2b. Process 2			kg/tonne input	
2c. Process 3			kg/tonne input	
2d. Process 4			kg/tonne input	
2e. Process 5			kg/tonne input	
2f. Process 6			kg/tonne input	
2g. Process 7			kg/tonne input	

3. Please provide the estimated energy use per process.

	Process name		Energy use		Details/remarks
3a. Process 1		Electricity		kWh/tonne input	
		Natural gas		MJ/tonne input	
		Hydrogen		MJ/tonne input	
		Others		kWh/tonne input	
3b. Process 2		Electricity		kWh/tonne input	
		Natural gas		MJ/tonne input	
		Hydrogen		MJ/tonne input	
		Others		kWh/tonne input	
3c. Process 3		Electricity		kWh/tonne input	
		Natural gas		MJ/tonne input	
		Hydrogen		MJ/tonne input	
		Others		kWh/tonne input	
3d. Process 4		Electricity		kWh/tonne input	
		Natural gas		MJ/tonne input	
		Hydrogen		MJ/tonne input	
		Others		kWh/tonne input	
3e. Process 5		Electricity		kWh/tonne input	
		Natural gas		MJ/tonne input	
		Hydrogen		MJ/tonne input	
		Others		kWh/tonne input	
3f. Process 6		Electricity		kWh/tonne input	
		Natural gas		MJ/tonne input	
		Hydrogen		MJ/tonne input	
		Others		kWh/tonne input	
3g. Process 7		Electricity		kWh/tonne input	
		Natural gas		MJ/tonne input	
		Hydrogen		MJ/tonne input	
		Others		kWh/tonne input	

3. Suggestions/remarks

If you have any further suggestions, literature recommendations or other remarks regarding this questionnaire, feel free to add them in the box below or share them via email. Many thanks for your contributions!