Impacts of allocation rules on chemical recycling

Consequences on the environment and maximum circularity of plastics

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Content

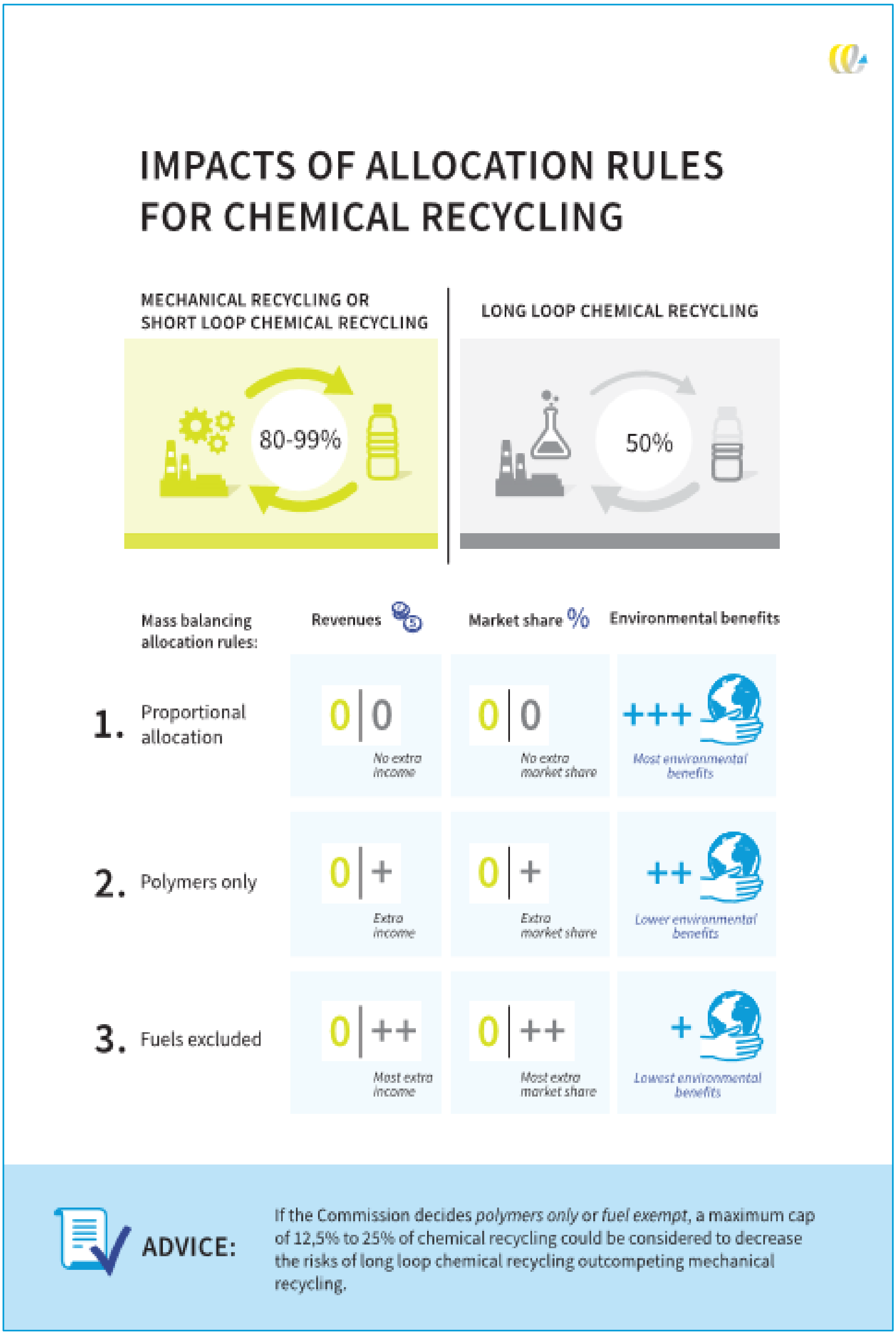
Summary

Allocation rules are required to match inputs (for example plastic waste) with multiple outputs (plastics, chemicals, fuels) from a recycling process and determine recycled content levels. For so called long-loop chemical recycling, there are three main options discussed at the moment in Europe: (1) proportional allocation, (2) polymers only and (3) fuels exempt. These methods differ in allocation freedom that chemical companies have to assign recycled content among the outputs (e.g. 100% recycled content in plastics and 0% in chemicals instead of 50% plastics and 50% chemicals).

Proportional allocation, the option with the least allocation freedom, has the lowest impact on the level playing field between long-loop chemical recycling and mechanical recycling and the largest potential environmental benefits. This report shows that in a scenario with more mechanical recycling, the maximum CO_2 benefits of plastics recycling in 2040 are 9 Mtonne higher than in a scenario where long-loop chemical recycling is dominant. Although long-loop recycling is desirable in some cases (in particular for waste that cannot be recycled mechanically or short-loop chemically), it is from an environmental perspective undesirable that long-loop chemical recycling is becoming dominant and buys up waste that can be recycled mechanically or short-loop chemically. Mechanical recycling and short-loop recycling convert plastic waste more effectively in recyclate and are therefore environmentally preferable. Also, with proportional allocation there is less ambiguity about the recycled content in the plastic outputs, which increases the transparency in the plastic recycling market.

Through allocation rules with the most freedom (fuels exempt), chemical recyclers can attribute the recycled content to products with the highest market values. These products may be composed from a small portion recyclates, but marketed as a higher percentage recycled. This will make it easier for chemical recyclers to assign the outputs with the highest values as being recycled and increase the financial benefits, while this is not possible for mechanical recyclers and short-loop chemical recyclers, which produce only one single output (plastics) and require no allocation rules.

If the Commission decides to implement options with larger allocation freedom (polymers only or fuel exempt), a cap on chemical recycling could be considered to decrease the risks of chemical recycling outcompeting mechanical recycling. A maximum of 12,5 to 25% long-loop recycling, based on the percentages which have been suggested in the Dutch transition Agenda, could be an option for such a cap. Furthermore, the Commission could consider to implement more norms on product groups that can meet the targets with mechanical recyclate. Current proposals for mandatory recycled content in food packaging give an incentive to direct waste plastics to long-loop chemical recycling.


IMPACTS OF ALLOCATION RULES FOR CHEMICAL RECYCLING
MECHANICAL RECYCLING OR SHORT LOOP CHEMICAL RECYCLING
80-99%
LONG LOOP CHEMICAL RECYCLING
50%
Mass balancing allocation rules:
Revenues
Market share %
Environmental benefits
1. Proportional allocation
0 | 0 No extra income
0 | 0 No extra market share
+++ Most environmental benefits
2. Polymers only
0 | + Extra income
0 | + Extra market share
++ Lower environmental benefits
3. Fuels excluded
0 | ++ Most extra income
0 | ++ Most extra market share
+ Lowest environmental benefits
ADVICE:
If the Commission decides polymers only or fuel exempt, a maximum cap of 12,5% to 25% of chemical recycling could be considered to decrease the risks of long loop chemical recycling outcompeting mechanical recycling.

1 Introduction

1.1 Background

Chemical recycling is a category of technologies that aim to bring plastics back to their original components (e.g. polymers, monomers, atoms), so that new plastics and other products can be made from these components. Waste plastics that are chemically recycled end up in multiple products from the same production process, including plastics and other chemical products.

For chemical companies, the output of recycled plastics is often more interesting than other substances, as recycled content targets are for now only under discussion for plastics (for PET bottles by 2025 and other bottles by 2030). Companies therefore wish to allocate the recycled content of outputs as much as possible to plastics. This administrative reallocation of the recycled content can be done through the use of ‘mass balance’ chain of custody. There are three main options discussed at the moment in Europe: (1) proportional allocation, (2) polymers only and (3) fuels exempt.

These options may have different consequences on the level playing field between chemical and mechanical recycling. Mechanical recycling processes plastic waste into secondary raw materials or products, where the chemical compounds of the plastics are not broken down. Although specifications of the quality of sorted waste plastic may differ, mechanical and chemical recycling can compete for the same plastic waste streams as feedstock for recyclate production.

As mechanical recycling on average leads to more environmental benefits and higher recycling yields than chemical recycling technologies, allocation rules stimulating chemical recycling may impact CO_2 reduction and circular economy targets. In this report we have therefore assessed the environmental impacts of the different allocation methods.

1.2 Objective

To determine the impacts of allocation rules (mass balances options) of the recycled feedstock input to the output product on environmental benefits and level playing field between different recycling technologies. More specifically, between technologies with high tractability and technologies with multiple outputs.

1.3 Outline

The outline of the report is as follows:

- In Chapter 2 we describe two different scenarios for plastic recycling in the EU and corresponding environmental impacts and recycling percentage: one scenario with high share of chemical recycling and a scenario with high share of mechanical recycling.
- In Chapter 3 we present the three main allocation methods under discussion at the moment and impacts on the level playing field.
- In Chapter 4 we present the conclusions.

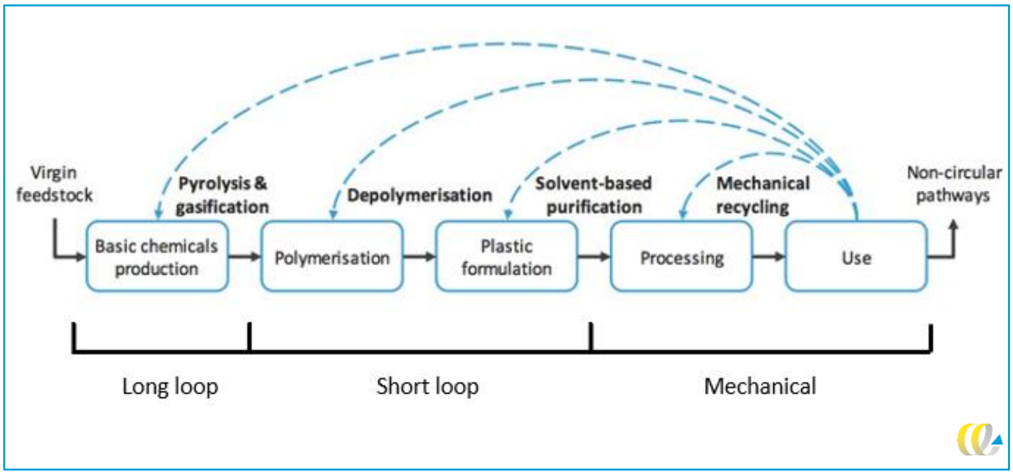
2 Recycling technologies and their environmental benefits

2.1 Different types of recycling techniques

There are three different categories of recycling methods: mechanical recycling, short-loop chemical recycling and long-loop chemical recycling (CE Delft, 2018). Mechanical recycling processes plastic waste into secondary raw materials or products, where the chemical compounds of the plastics are not broken down. The waste is mechanically sorted, separated, washed, grinded, and melted by an extruder. Then, in the same process, plastic granules are being established by the process of compounding. This form of recycling is particularly suitable for waste streams of one type of relatively clean plastic.

Chemical recycling aims to bring back plastics to their original components (e.g. polymers, monomers, atoms), so that plastics and other product can be made from these components (KIDV, 2017).[1] Short-loop recycling methods produces outputs (e.g. polymers, monomers or oligomers) that only need a few process steps to produce new plastic products. The output products from long-loop recycling techniques are brought back further in the plastic production chain to basic chemicals (see Text box 1).

Figure 1 – Production steps of recyclates for different recycling techniques (CE Delft, 2019)[2]



[1] An advantage of chemical recycling is that it results in raw materials. These raw materials can be used for other high quality plastic applications, such as food packaging or deposit bottles. However, for these chemical techniques more energy is needed. As a result, chemical recycling techniques (especially pyrolysis) tend to be more costly and more impactful from an environmental point of view than mechanical recycling (CE Delft, 2019).

[2] CE Delft, 2019. Chemische recycling in het afvalbeleid, Delft: CE Delft.

Text box 1 – Categories of chemical recycling

Chemical recycling can be categorized in four techniques, being solvent-based extraction, depolymerization, gasification, and pyrolysis:

Short-loop chemical recycling, for which no mass balancing is required, are:
1. Solvent based extraction. This method uses chemicals (as a solvent) to resolve plastics. After which, the polymer chain is being cleansed and can be recovered. However, this technology can also be classified as mechanical recycling, as no chemical reaction takes place.
2. Depolymerization. In depolymerization polymers are being deduced to monomers (or oligomers). These monomers are similar to virgin monomers and can therefore be easily implemented in the production chain of plastics.

Long-loop chemical recycling are (mass balancing required):
3. With pyrolysis, plastics are being heated (without the interaction with oxygen) to separate heavier and lighter molecules. The products from pyrolysis can be produced in the same way as other oils to generate new polymers.
4. Gasification uses a thermal process with high temperatures (through steam, oxygen or air). The plastic products are decomposed to (syn)gasses, which can then be used to produce new polymers.

Solvent-based extraction and depolymerization produce outputs (e.g. polymers, monomers or oligomers) that only need a few process steps to produce new plastic products and do not produce multiple outputs. Therefore no mass balance method is required. Pyrolysis and gasification are known as long-loop chemical recycling techniques. The output products from long-loop recycling techniques are brought back further into the plastic production chain. Resulting into basic chemical products or oils. To make new plastic products from these inputs, more steps are needed and mass balance is required.

2.2 The P2P yields of plastic recycling techniques

A concept that helps to assess the effectiveness of different plastic recycling techniques is the plastic-to-plastic yield (P2P yield). The P2P yield quantifies the amount of new plastics that can be produced from plastic waste sent to recycling (i.e. a weight share). These P2P yields determine (alongside the sorting and separation yields) how efficiently plastic waste can be transformed to recyclate.

Presently, the plastic waste feedstock is much lower than total plastic consumption. In Europe 47,8 Mtonne of plastics were consumed, while only 25 Mtonne of plastic waste were discarded (Plastic Europe, 2018). The amount of plastic waste is lower than consumption, because plastics end up in products with a long lifetime (e.g. cars and buildings), while plastic consumption is growing. These numbers for plastic waste could be considered as conservative, whereas 40% of plastics are unaccounted for in statistics when comparing the plastics that are put on the market and the volume of plastic waste collected (SYSTEMIQ, 2022).

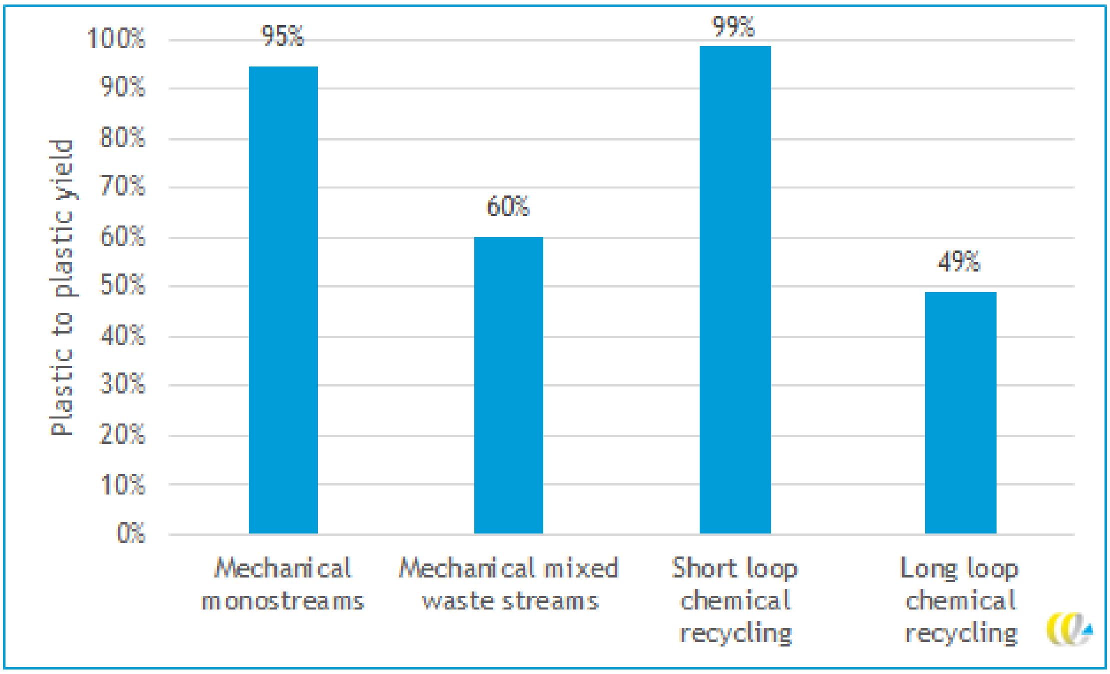
If we take a growth rate of 0.6% annually for plastic consumption and 1.5% for the production of waste, which were calculated by the VNO-NCW in their plastic outlook VNO-NCW (2020), 55 Mtonne plastics are consumed in 2040 while 35 Mtonne of plastic waste is disposed.

In order to achieve as high as possible recycling rates and environmental benefits, it is important that plastic waste is processed at optimum (with low sorting/separation losses and a high P2P yield). Consequently, it is important that the right composition of plastic recycling techniques is chosen. The composition of plastic recycling techniques influences the environmental impact of plastic recycling, because the P2P yields differ significantly across these recycling techniques.[3]

Figure 2 shows that the P2P yield of mechanical recycling has a range of 60% (mixed plastics) to 95% (mono materials). For short-loop chemical recycling, the P2P yield is approximately 99%. The P2P yield of long-loop chemical recycling is relatively low, and accounts 34% for gasification and 49% for pyrolysis (although figures for gasification are uncertain). Based on these P2P yields, long-loop chemical recycling needs more plastic waste for 1 kg recyclate than mechanical recycling and short-loop chemical recycling (CE Delft, 2022). Given the scarcity of plastic waste, this is undesirable.

Having said this, long-loop chemical recycling can be beneficial in some situations. Long-loop chemical recycling may process plastic waste that cannot be recycled through mechanical recycling (although the requirements for pyrolysis can be demanding as well, such as polyvinyl chloride limits). Moreover, long-loop chemical recycling can offer high quality recyclate (virgin quality) that can be used for applications with strict requirements, such as food packaging. However, given the limited availability of plastic waste and relatively low P2P yields, it is questionable if recyclate should be directed to a large extent to product groups with strict requirements.

Figure 2 - P2P yields of different plastic recycling techniques (CE Delft, 2022)*



* Figures for gasification are excluded, because these figures are uncertain. Therefore, the P2P yield of long-loop chemical recycling is based on the P2P yield of pyrolysis, which is 49%.

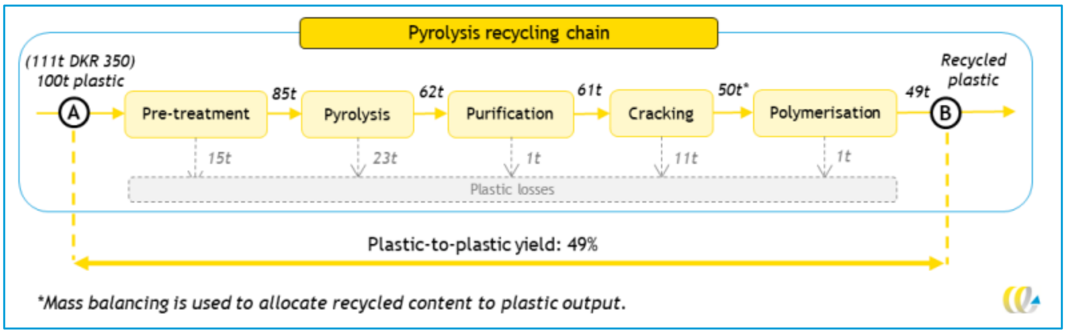
3 The P2P yields have been based on a previous study of CE Delft: Monitoring chemical recycling. How to include chemical recycling in plastic recycling monitoring? - (CE Delft, 2022).

Text box 2 - Example: pyrolysis of DKR 350 into PE

In this example, we illustrate how the plastic-to-plastic yield is built up for long-loop chemical recycling, and explain why the plastic-to-plastic yield is lower for long-loop chemical recycling.

DKR 350 (mixed plastic waste) is treated with a pyrolysis technology, as illustrated in Figure 3. 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 3 - Breakdown of the plastic to plastic yield of a pyrolysis recycling chain targeting PE production from DKR 350



- 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 3). 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 (CE Delft, 2022).

2.3 Recycling scenarios

The environmental benefits of mechanical and short-loop chemical recycling can be illustrated more concretely by applying two scenarios to the European plastic market.[4] The European scenarios have been based on an extrapolation of representative outlooks which have been developed in the Netherlands, which is a country with a large plastics industry (industrial clusters in Rotterdam Harbour, Zeeland and Limburg), The plastic production in the Netherlands is 5,3 Mton and the consumption circa 2 Mton. The Dutch government and industries have developed two scenarios for future plastics recycling and

[4] In the scenario analysis, Europe also contains the plastic markets of Switzerland and Norway.

biobased production, differing to a large extent in market penetration of mechanical recycling and long-loop chemical recycling:

Scenario 1: Dutch Plastic Transition Agenda (more mechanical recycling) 2018

The first scenario is the transition agenda (Ministerie Van I&W, 2018). The transition agenda has been developed as a part of the Dutch governmental program 'Netherlands circular in 2050'. To speed up the transition to a circular economy, the government has identified which steps are necessary to make the Dutch economy more sustainable. The goal is to reduce the use of virgin materials by 50% in 2030 and to realize a complete circular economy in 2050. In this process, five transition agendas have been formed for the most environmental burdensome sectors, with the plastics sector being one of them. A transition team, consisting of scientists, policy makers and representatives of the industry, is responsible for the execution and monitoring of the transition agenda plastics. Goals have been formulated for 2030 and aim that 25% of the discarded waste will be recycled chemically in 2030, and 75% will be recycled mechanically.

Scenario 2: Dutch Roadmap Chemical Recycling 2021

The second scenario is the roadmap chemical recycling. The chemical recycling roadmap[5] was published in 2021 (three years later than the transition agenda) and adopted by the Dutch government (Rebel Group & Vno-Ncw Mkb, 2020). The roadmap shows ways in which the Netherlands can facilitate chemical recycling and extend the market share of chemical recycling. Chemical recycling is regarded as being desirable, because it can recycle plastic waste that is ineligible for mechanical recycling. The roadmap focusses on 555 kton recyclate from chemical recycling (10% of the production of plastics in the Netherlands) and needs 1,000 to 1,500 kton of plastic waste input, while the amount of plastic waste in the Netherlands is 1,058 kton a year.[6] This latest plan focusses on a lot of import but this will be problematic as other countries will also stimulate recycling of material. This would imply a complete shift from mechanical recycling to chemical recycling in the Netherlands.

Maximum achievable recyclate production in Europe based on two scenarios

We have extrapolated the Dutch scenarios to the European market in order to determine the maximum achievable CO_2 reduction. The maximum achievable CO_2 reduction would be a situation in which all available plastics are recycled (mechanically and or chemically). This is an extreme scenario, in which plastics are separated and sorted close to optimum. In reality, it will be rather challenging to acquire these separation and sorting yields. The numbers in these scenarios should be interpreted as being indicative for the potential of the plastic recycling industry. Rather than being a reliable prediction.

In 2040, it is expected that around 55 Mtonne of plastic products will be consumed in Europe and 35 Mtonne of waste plastics discarded. As discussed earlier, the amount of waste plastics is lower than consumption, because plastics can end up in products with a higher lifetime (not becoming waste directly) while consumption is growing. Not all the 30 Mtonne of waste plastics can be sent to recyclers, as sorting and separation losses occur in the collection process. Maximum sorting and separation yields range from 50% (automotive,

[5] Roadmap chemische recycling kunststof 2030 Nederland | Rapport | Rijksoverheid.nl www.rijksoverheid.nl/documenten/rapporten/2021/03/12/bijlage-1-roadmap-chemische-recycling

[6] Source: Plastics Europe (2020).

one; F. Ardolino; U., 2022) to 70% (packaging, (Strategy&, 2022) and 75% (agriculture, (Circular Plastics Alliance, 2020). Based on these conversion rates, around 24 Mtonne can maximum be sent to recycling in 2040.

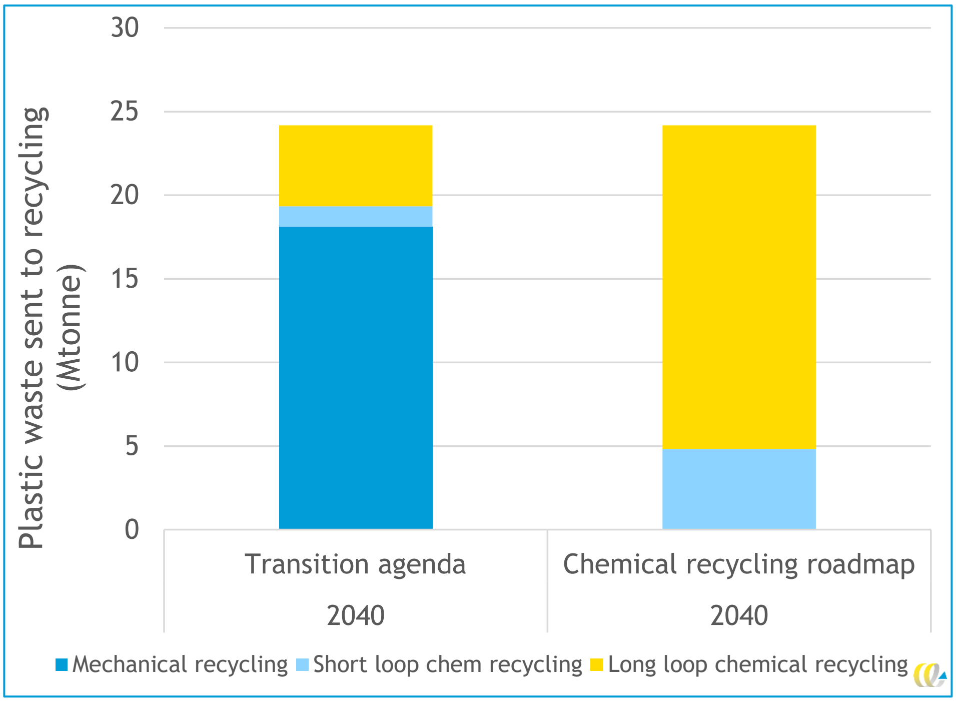
Table 1 – Theoretical maximum available plastic sent to recyclers in 2040

Category	Waste plastics 2040 (Mtonne)	Maximum seperation and sorting yield (%)	Maximum sent to recycling 2040
Packaging	21,4	70%	15,0
Agriculture	1,8	75%	1,4
Electronics	2	70%	1,4
Automotive	1,8	50%	0,9
Others	7,9	70%	5,5
Total	**35**		**24**

Sources: (Strategy&, 2022), (Arena, F. a. G. F. C. U., 2021), (Circular Plastics Alliance, 2020), (Arena, G. F. C. F. a. U., 2022).

In the transition agenda, 75% of these sorted plastics are sent to mechanical recycling, while 20% is being sent to long-loop chemical recycling and 5% to short-loop chemical recycling. In the roadmap chemical recycling, all the waste is directed to chemical recycling; 80% is sent to long-loop chemical recycling and 20% to short-loop. The amounts (in Mtonne) for 2040 are presented in Figure 4 below.

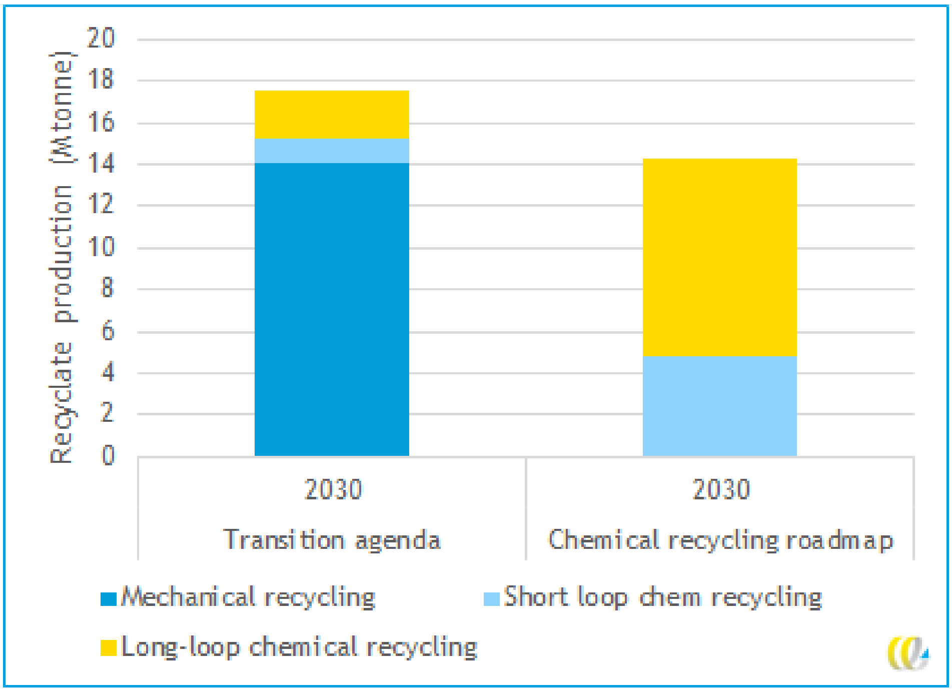
Figure 4 – Theoretical maximum available quantities of plastic waste sent to recycling (Mtonne)



Not all of the sorted plastic waste that is sent to recyclers becomes recyclate, due to losses in the recycling process, which differ between the recycling technologies (see Figure 2). Based on the shares of mechanical and chemical recycling, and the plastic to plastic yields, we have calculated the maximum amount of recyclate that can be produced in each of the scenarios.

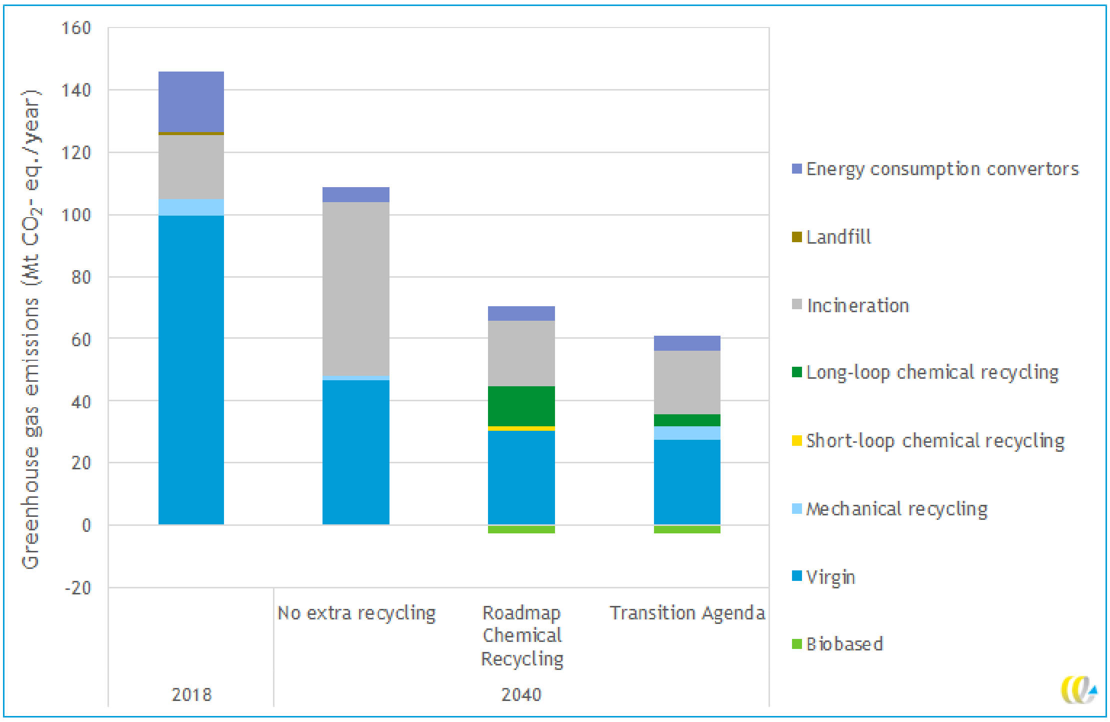
The maximum yield of recyclates is 18 Mtonne (2040) in the transition agenda scenario.
In the chemical roadmap scenario with more long-loop recycling, the total amount of recyclate is lower with 14 Mtonne (2040), given the lower P2P yield of long-loop chemical recycling technologies.

Figure 5 - Maximum achievable recyclate production in 2040 (Mtonne)



The variations in the market share of recycling techniques across the scenarios have implications for their environmental impact. Corresponding to our previous report (Ce Delft, 2022), we have calculated the average CO_2 emissions for every recycling technique.
This results in a CO_2 emission of approximately 68 Mtonne in 2040 for the chemical roadmap scenario. The CO_2 emissions in the transition agenda scenario are 59 Mtonne in 2040.
As can be deduced from the results, the environmental benefits are more substantial for the transition agenda in comparison to the chemical recycling roadmap.

Figure 6 - CO_2 reduction in Mton per scenario for 2040



The higher P2P yield of mechanical recycling also results in higher achievable recycling rates. In the transition agenda the maximal recycling rate is 32% in 2040, while the maximum achievable recycling rate in the chemical recycling roadmap is 26% in 2040.

Figure 7 - maximum achievable plastic recycling percentage per scenario (plastic recyclates as a share of plastic consumption)

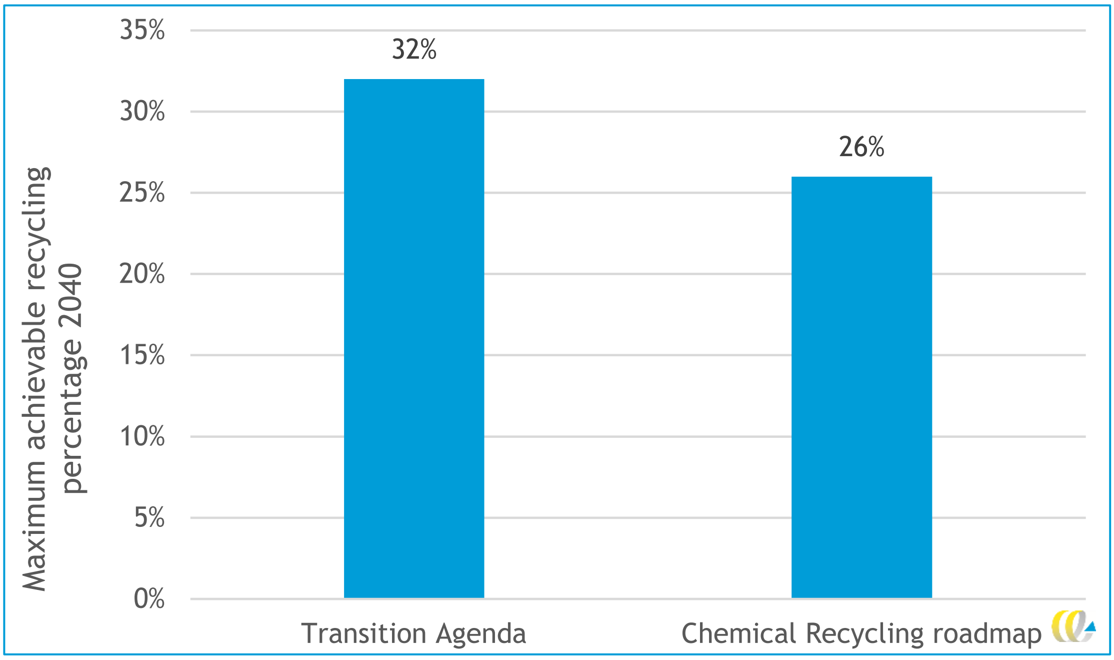
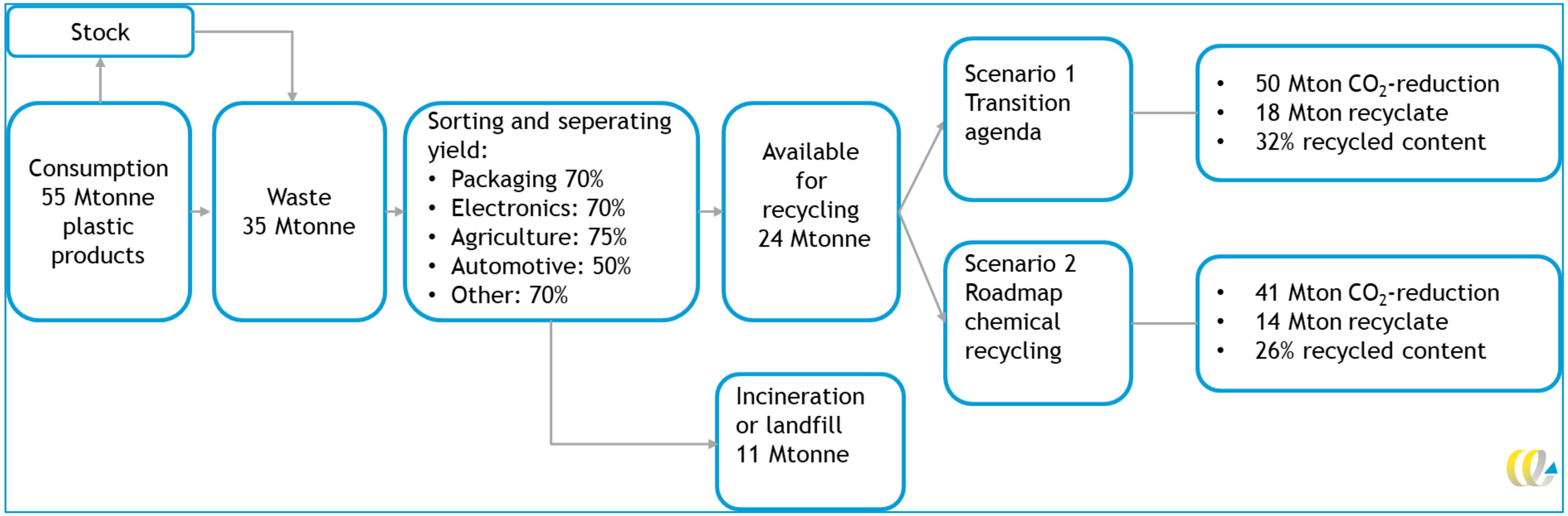


Figure 8 - Theoretical maximum achievable effects of European plastic recycling market in 2040 based on two roadmaps for (chemical) recycling of plastics



2.4 Conclusion

The scenarios, which both have been developed in a cooperation between the government and chemical industry, show that a larger share of long-loop recycling results in lower environmental benefits and maximum recycling rates. Although long-loop recycling is desirable in some cases (in particular for waste that cannot be recycled mechanically or short-loop), it is important that long-loop chemical recycling is not becoming dominant and competes for waste that can be recycled mechanically. In the next chapter, we discuss the potential impacts of allocation rules on the level playing field between chemical and mechanical recycling technologies.

Table 2 - Summary of scenarios

Scenario	Recycling share	Maximum CO_2 reduction compared to no extra recycling	Recycling rate
1 Transition Agenda	Mechanical recycling 75%	50 Mtonne (2040)	32% (2040)
	Short-loop chemical recycling: 5%		
	Long-loop chemical recycling: 20%		
2 Roadmap Chemical Recycling	Mechanical recycling 0%	41 Mtonne (2040)	26% (2040)
	Short-loop chemical recycling: 20%		
	Long-loop chemical recycling: 80%		

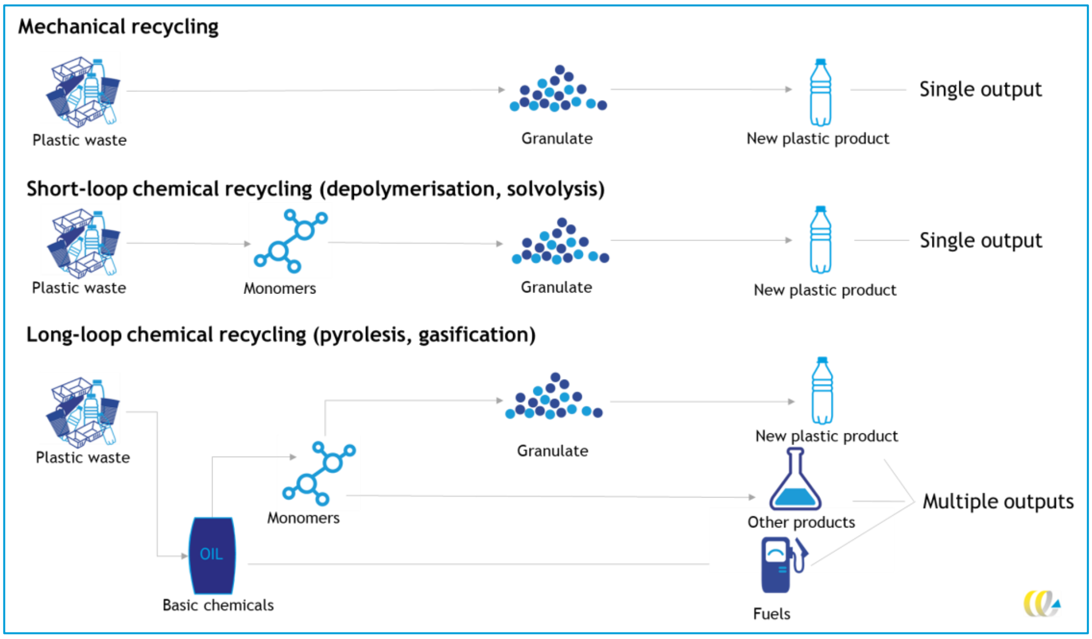
3 Impact of allocation rules on level playing field

3.1 Mass balance system

As discussed in Chapter 1, multiple products are produced from plastic waste in long-loop chemical recycling processes. An accounting method is therefore required to calculate the recycled portion in the plastic output products. Long-loop chemical recycling produces basic chemical products that can be integrated with chemical industrial complexes that process fossil raw materials. For example, pyrolysis oil (after upgrading) can be mixed with fossil naphtha. This mixture of recycled and virgin content can be processed together in a steam cracker, producing various chemical products (e.g. ethylene) that are converted in various products (ZWE, 2021). Physically, the recycled content is spread out over all these products (and intermixed with the virgin compartments). In this situation, it is not feasible to physically separate the recycled and non-recycled content (PE, 2021).

For mechanical recycling and short-loop chemical recycling this is more straight-forward. With mechanical recycling, plastic waste is sorted and cut into small pieces (being plastic granulate). This granulate is, then, used directly to produce new plastic products. All plastic waste is, thus, used to produce new plastic outputs (and not for other products). A similar rhetoric could be held for short-loop chemical recycling. With short-loop chemical recycling, plastic waste is reduced to polymers, oligomers or monomers that can be used to produce new plastic products within a few steps. In general, short-loop chemical recycling is executed in fabrics that only produce plastic output products. So all recycled content is used to produce new plastic products. As a result, there is less ambiguity about the recycled content in the outputs of mechanical and short-loop chemical recycling and mass balancing is not required.

Figure 9 - Recycling methods



To attribute the right portion of recycled input to the specific output a ‘chain of custody’ model can be employed (CE Delft, 2022). This report focuses on the mass balance system, which is an accounting system to track the recycled materials when they are blended with virgin fossil materials. Additionally, it can be used to allocate recycled input to specific outputs. The recycled content in the output should not be larger than the amount of recycled inputs.

3.2 Allocation rules and credit transfers

The allocation rules prescribe how the recycled content is attributed to the specific output products from a batch. There are several allocation rules, but we focus in this report on three allocation rules, as these allocation rules are currently being discussed for potential legislation (EMAF, 2019):

- **Proportional**: quantities of recycled input are attributed to each output product in the same portion as what they represent in the total input, i.e. recycled content claims cannot be transferred from one output product to another.
- **Polymers only:** the theoretical amount of recycled plastic in outputs that are directly linked to the production of polymers can be freely allocated among these outputs. So recycled inputs can be allocated freely amongst polymer outputs.
- **Fuel-use exempt (excluded):** fuel use in the process and co-products produced and used as fuels are excluded. The remaining theoretical amount of recycled plastic may be freely allocated among the remaining output products.

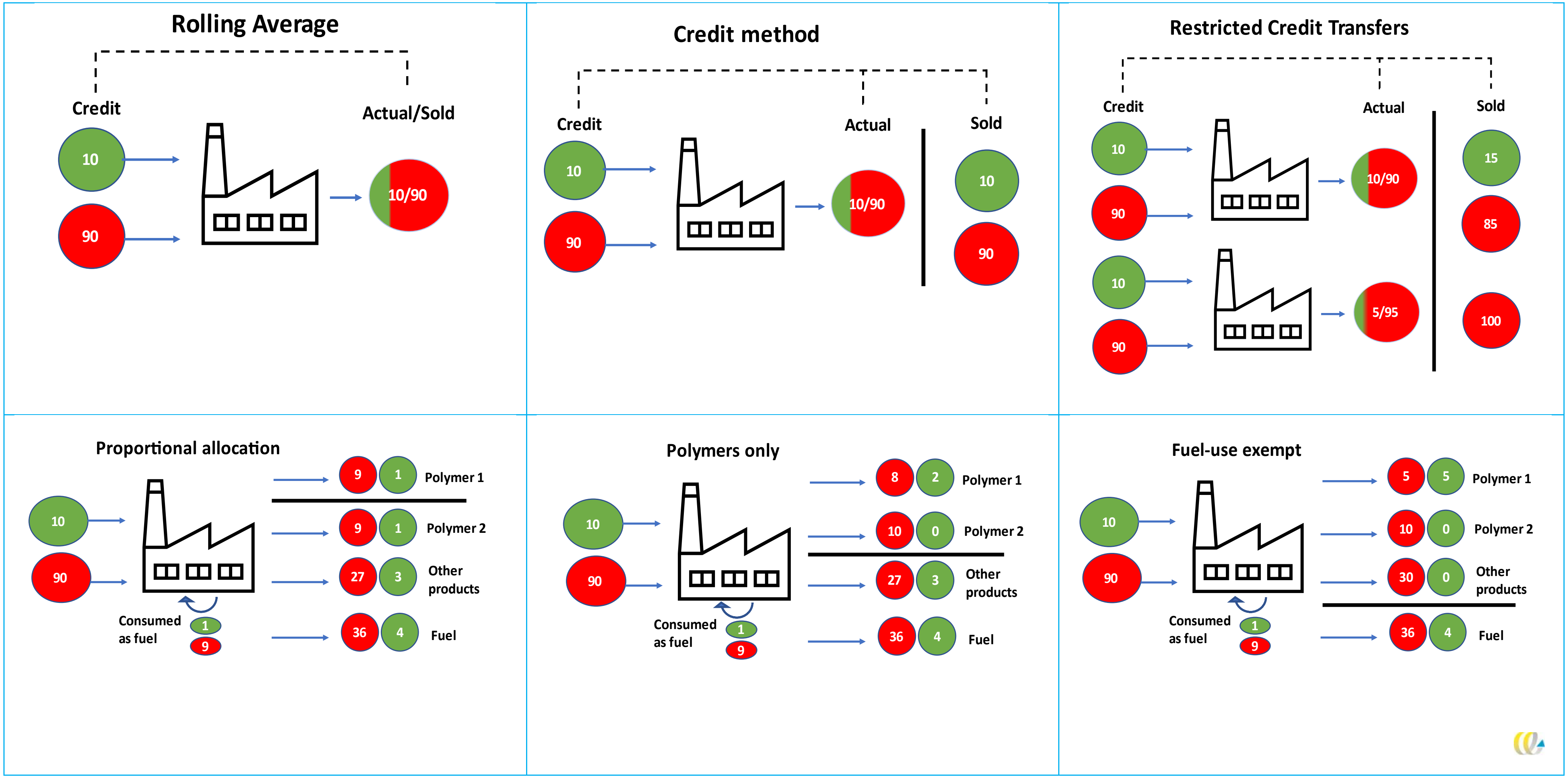
An additional issue is whether recycled content credits can only be attributed within a chemical production site, or whether the credits can be transferred/aggregated across different sites through a credit transfer system. This last option (multi-site transfers) could make small-scale chemical recycling 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.

Presently, three main variations are being discussed with regard to credit transfers (see also Figure 10).

- **Rolling average within a chemical production line:** product is sold as being x% recycled based on the input ratio recyclate/virgin plastics. This percentage is attributed to the complete batch.
- **Credit method within a specific organization:** the input ratio recyclate/virgin plastics leads to credit tokens. These credits can be freely allocated to the plastic output products within a specific organization. So if the proportion recyclates/virgin plastics is 10% (with a batch of 100). They can place ten plastic output products in the market as recycled.
- **Nationally restricted credit transfers:** Credit tokens for recycled input are transferable between organizations within a country.

The credit system has a large impact on traceability and transparency of recycled content in plastic outputs. Credit transfers are important for determining which portion of recycled content is actually in the plastic outputs. For example, in a restricted credit transfer system organizations can market their products as recycled by buying credits, while the recycled portion is actually low or even zero. This makes it more difficult for consumers to identify where the recycled portion is coming from.

Figure 10 - Visualization of allocation and credit transfer methods based on DOW paper (Dow, 2022)

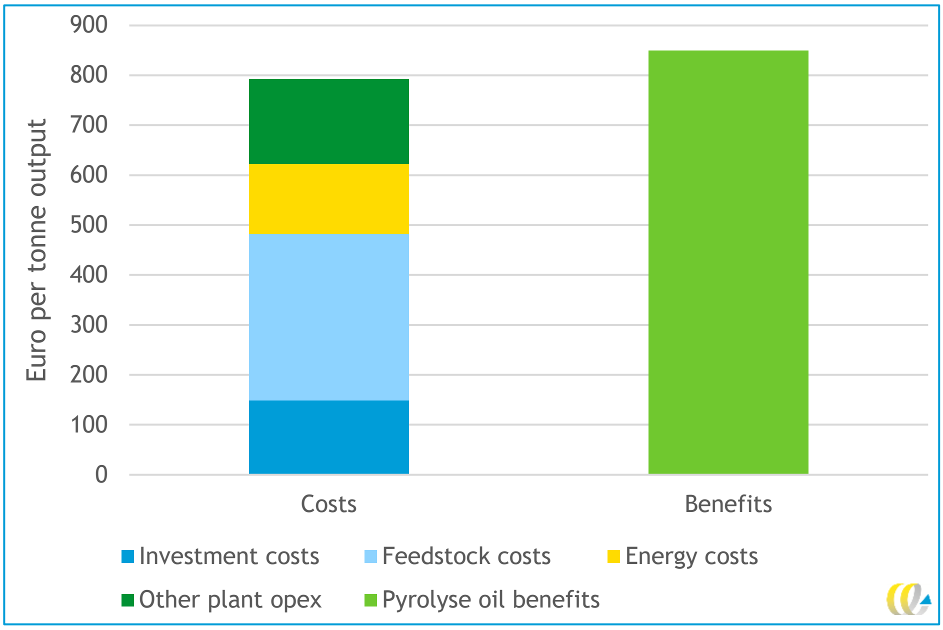


3.3 Impact on level playing field

Chemical recycling and mechanical recycling compete with each other for market share under the constraint of available feedstock. The mass balance system could facilitate a competitive advantage for long-loop chemical recycling.

At the moment, the profitability of chemical recycling technologies is to a large extent depending on the output price of the recycling process. An actual but illustrative business case, based on an initiative in the Rotterdam Harbour area[7], is presented in Figure 11 below.

Figure 11 – Costs and benefits of a pyrolysis oil plant in the Rotterdam Harbour area (euro per tonne, 30 Mtonne output, 10% return on investment, lifetime 15 years)



Source: (Pryme, 2022).

The profitability of the project is very much depending on the pyrolysis oil benefits. This price is correlated to the naphtha price and very volatile. The figure shows that the price of naphtha was in most cases lower than the required 800 euro per tonne for a profitable business case. The green mark-up for pyrolysis oil compared to fossil naphtha is therefore very important for future investments in pyrolysis. Also, there is a relationship between the naphtha price and the cost of plastic feedstock. Correspondingly, the price of naphtha has big implications for the business case of chemical recycling and the market shares of the plastic recycling technologies.

7 https://pryme-cleantech.com/uploads/downloads/Pryme-Q4-2021-Presentation.pdf

Figure 12 - Naphtha price (Euro per tonne)

Source: (Insee, 2023).

Through mass balancing with allocation freedom and credit transfers, chemical recyclers can attribute the recycled content to products with the highest market values and increase the willingness to pay for e.g. pyrolysis oil. The products may be composed from a small portion of recyclates, but marketed through the mass balance system as a higher percentage recycled. This will make it easier for chemical recyclers to assign the outputs with the highest values as being recycled and increase the financial benefits, while this is not possible for mechanical recyclers and short-loop chemical recycling.

Allocation freedom (and credit transfers) may increase the market share of long-loop chemical recycling, because it offers a competitive edge for chemical recycling in the high quality plastic output market. The chemical recycling companies can use this competitive advantage to acquire more resources and investments, which helps them to buy up more recyclate and increase their market share.

In the case of proportional recycling and a rolling average, this risk is very low. The chemical roadmap scenario from chapter 2 is therefore very unlikely when this allocation method is chosen. In case of polymers only and fuels exempt, the risk is higher that a chemical roadmap scenario will emerge. In order to reduce these risks, a cap (maximum) on chemical recycling could be considered.

A maximum of 12,5 to 25% long-loop recycling could be an option. This maximum is based on the percentages of the Dutch transition Agenda (see Chapter 2). Such a cap would ensure that long-loop chemical recycling does not become too dominant. Furthermore, the Commission could consider to implement more norms on product groups that can meet the targets with mechanical recyclate. Current proposals for mandatory recycled content in food packaging give an incentive to direct waste plastics to long-loop chemical recycling.

3.4 Hypothetical case study

We have illustrated the potential impact of allocation freedom on the level playing field in the plastic recycling market through a hypothetical example. In this example, we compare plastic waste that can be sent to a mechanical recycling company with pyrolysis input in steam cracker under different allocation rules:

- proportional allocation, rolling average;
- proportional allocation, credit transfer;
- polymers only, credit transfer;
- fuels exempt, credit transfer.

The steam cracker outputs of a chemical recycling company are derived from Ullmann's Encyclopaedia of Industrial Chemistry (Eunomia, 2021). The additional revenues for chemical recyclate are based on the mark-up prices of mechanical recyclate relative to virgin plastics. Presently, prices for chemical recyclate are unknown, because the chemical recyclate market is an emergent property. In our estimation, we have taken the virgin grade mark-ups of high quality post-consumer transparent mechanical recyclate to estimate the mark-up price of chemical recyclate. We have taken mark-ups of 1,100 euro per tonne of 100% recycled HDPE recyclate and 900 euro per tonne 100% recycled PP. Based on the mark-up prices and the quantities of chemical recyclate, we have calculated the additional revenues per allocation rule. The additional revenues are based on 100 ton inputs (95 ton virgin and 5 ton pyrolysis oil). The results of this analysis are presented in Figure 13.

Additional incomes long-loop chemical recycling through administrative reallocation

In a situation with proportional allocation and a rolling average, chemical recyclers can only sell their products based on the actual recycled content in the output product. In this scenario, there is no administrative reallocation. Therefore, the additional revenues due to administrative reallocation are non-existent for the chemical recyclers and there is a level playing field between mechanical and short-loop chemical recycling. This is illustrated in Figure 13.

In case of credit transfers and proportional allocation, chemical companies are allowed to sell output tokens as recycled content. Mechanical recycling companies are not part of the mass balance system, and can therefore not earn extra money with administrative reallocation of recyclate.

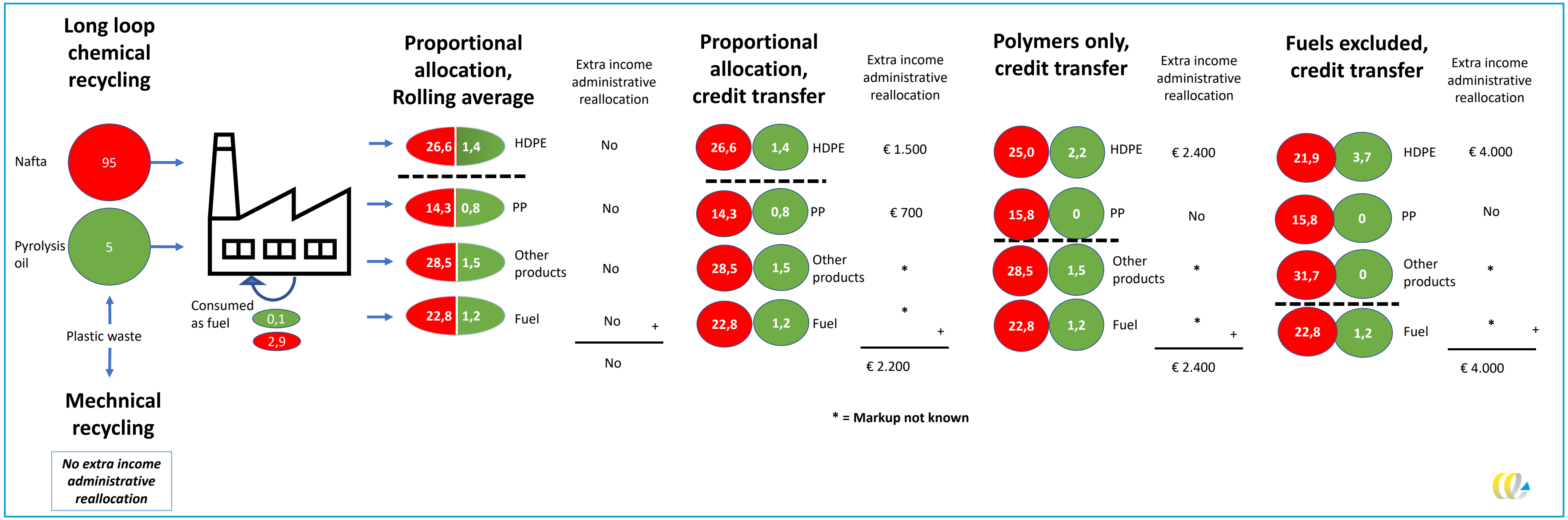
In our hypothetical example of 95 ton virgin and 5 ton pyrolysis oil, a credit transfer will increase earnings of 5 kton pyrolysis inputs by 2,200 euro (see Figure 13). The extra earnings are very case specific and depending on the amount of pyrolysis oil in the cracker. If more pyrolysis oil would be inserted in the cracker (e.g. 10% instead of 5%), there may be a smaller markup of a credit transfer compared to rolling average and thus a lower impact on the level playing field with mechanical recycling.

When comparing polymers-only with proportional allocation, the impact of the allocation rules on the revenues of chemical recyclers is relatively shallow. This can be explained by looking at the prices for recyclate. Currently, the mark-up for HDPE and PP recyclate is quite similar. Correspondingly, shifting recyclate units between these plastic output products does not provide a lot of additional revenues. In our example (based on polymer prices of HDPE and PP), the additional revenues for chemical recyclers are € 200.

The impact of allocation freedom of becomes more extensive, when recyclate in other products can be allocated to polymers. By allocating recyclate from other products to polymers chemical recycling companies can earn more money, because recyclate usage in polymers is valued higher. In our hypothetical example of the fuels-exempt scenario, chemical recycling companies can earn 1,600 euro at most by allocating recyclate units from other products to polymers. This 1,600 euro does not correct for price mark-ups for other products.

The additional revenues from administrative reallocation cause a maximum of 4,000 euros of additional revenues for chemical recycling companies (relatively to mechanical recycling companies).This hypothetical case study shows that administrative freedom could favour the market share of chemical recycling by providing additional revenues to chemical recycling companies

Figure 13 - Potential additional revenues for recyclate per allocation method (quantities in ton output)



* Source quantities: (Eunomia, 2021).

* Source prices: own estimates based on mark-up high quality mechanical recyclate.

3.5 Other considerations

A mass balance approach is defendable, as there seems to be a substantial correlation between the plastic-to-plastic yields and the CO_2 emission reduction (CE Delft, 2022). However, pyrolysis in particular uses considerably more energy than mechanical recycling, which is met by the losses of plastic in the process. If chemical companies decide to use an additional external source of energy for the process, pyrolysis processes could increase their yields based on mass balance approach. Therefore a combined mass and energy balance approach might be preferable over a mass balance approach.

3.6 Conclusions

Through mass balancing with allocation freedom and credit transfers, chemical recyclers can attribute the recycled content to products with the highest market values and increase financial benefits, while this is not required for mechanical recyclers and short-loop chemical recycling. In case of polymers only and fuels exempt allocation method, the risk is higher that a chemical recycling scenario will emerge. A cap (maximum) on chemical recycling could be considered.

4 Conclusions

The main objective of this study was to determine the impacts of allocation rules (mass balances options) of the recycled feedstock input to the output product on environmental benefits and level playing field between mechanical and chemical recycling.

The main conclusions are:
- A larger share of long-loop recycling technologies result in lower environmental benefits and reduced maximum recycling rates. Although long-loop recycling is desirable in some cases (in particular for waste that cannot be recycled mechanically or short loop), it is important that long-loop chemical recycling is not becoming dominant and competes for waste that can be recycled mechanically.
- Through mass balancing with allocation freedom and credit transfers, chemical recyclers can attribute the recycled content to products with the highest market values. These products may be composed from a small portion recyclates, but marketed through the mass balance system as a higher percentage recycled. This will make it easier for chemical recyclers to assign the outputs with the highest values as being recycled and increase the financial benefits, while this is not possible for mechanical recyclers and short-loop chemical recycling.
- Proportional allocation reduces the risk of scenarios with a large share of long-loop chemical recycling. In such a scenario, the maximum CO_2 benefits of plastics recycling are 9 Mtonne lower than in a scenario with more mechanical recycling. Both scenarios have been developed in a cooperation between the chemical industry and Dutch government and are regarded as realistic according to those parties. Also, with proportional allocation there is less ambiguity about the recycled content in the plastic outputs, which increases the transparency in the plastic recycling market.
- If the Commission decides polymers only or fuel exempt, a cap on chemical recycling could be considered to decrease the risks of chemical recycling outcompeting mechanical recycling. Furthermore, the Commission could consider to implement norms on product groups that can meet the targets with mechanical recyclate. If fuels exempt will be allowed for long-loop chemical recycling, we advise to introduce another kind of regulation to secure that mechanical and short-loop chemical recycling will stay the dominant recycling option to secure maximum CO_2 reduction and circularity score.
  A maximum of 12,5 to 25% long-loop recycling, based on the percentages which have been suggested in the Dutch transition Agenda, could be an option for such a cap.

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