Chemical recycling of plastic packaging materials

Analysis and opportunities for upscaling

Netherlands Institute
for Sustainable Packaging

Colophon

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Background reports:

An analysis of the production costs and gross profits of four chemical recycling processes, TNO, October 2018.

An exploration of chemical recycling, CE Delft, September 2018.

Reading guide

You are reading the report “Chemical recycling of plastic packaging materials: analysis and opportunities for upscaling.” In this report, we describe the steps that have to be taken to scale up the chemical recycling of plastic packaging materials in the Netherlands. The chemical recycling of plastic packaging materials is promising, because it has the potential to facilitate the recycling of plastic waste streams that are currently difficult or impossible to recycle using mechanical recycling methods. Furthermore, some forms of chemical recycling result in recyclate that can be used for food packaging.

This analysis was written for the representatives of chain parties in the waste sector and the chemical industry who are tasked with developing the Action Plan Chemical Recycling, as mentioned in the Transition Agenda for Plastics[1]. The findings, conclusions and measures outlined in this document offer guidelines for stakeholders in the chain to scale up the chemical recycling of plastic packaging materials.

“Chemical recycling of plastic packaging materials: analysis and opportunities for upscaling” consists of two main parts:

- **Part 1 “Conclusions and measures for upscaling”**: Chapter 1 provides an overview of the steps that stakeholders have to take to scale up the chemical recycling of plastic packaging materials. Chapter 2 summarises the key findings and conclusions from the analysis (part 2).

- **Part 2 “Analysis of the chemical recycling of plastic packaging materials”**: Part 2 forms the foundation to support the conclusions and measures for upscaling. This analysis provides answers to the following questions, among others: what is the environmental impact of the chemical recycling techniques that were studied? What are the process costs of demonstration processes? What are the barriers and opportunities in terms of policies and regulations?

The attachments contain background information on the project approach, a substantiation of the objectives and motivation of this project and a clarification of how the reflection on the analysis and this report has been organised.

[1] As part of the government-wide Circular Economy programme, the signatories of the Raw Materials Agreement have developed Transition Agendas for, among other things, plastic (published in January of 2018).

Contents

Part 1: Conclusions and measures for upscaling

1 Measures to scale up the chemical recycling of plastic packaging materials

1.1 Introduction

Stakeholders in the plastic packaging chain have the shared ambition to eventually close the chain, both in terms of the use of raw materials and in an economic sense. It is possible to increase the volume of recycled plastic and the quality of the recycling process by optimising existing collection and processing systems. By doing so, however, we will eventually encounter the limitations of these systems[2]. A system change with a potentially major impact on the quantity and quality of recycled plastic is the chemical recycling of plastic packaging materials. Chemical recycling techniques have the potential to improve and increase the recycling of plastic packaging materials and raise the quality of the recyclate to that of virgin plastics or raw materials. In order to realise the circular use of raw materials and reduce the emission of CO_2, the Transition Agenda for Plastics has defined the ambition to realise an annual output of 250 kt with chemical recycling by the year 2030.

The chemical recycling of plastics and plastic packaging materials seems promising, yet there still exist some gaps in our knowledge of these processes: which chemical recycling techniques are most promising? Does chemical recycling lead to a reduced environmental impact? Is chemical recycling economically viable? What obstacles and opportunities are there in terms of policies and regulations? In this analysis, we will answer these questions specifically for plastic packaging materials. Although chemical recycling can also be used for plastic products, that falls outside the scope of this KIDV analysis. In the fall of 2018, VNO-NCW will begin implementing the measures outlined in this analysis and develop them further in collaboration with the companies involved. VNO-NCW will strive to work together with chain partners in order to realise chemical recycling capacity for the plastic waste stream in the Netherlands that will process both plastic packaging materials and plastic products.

In this first chapter, we will outline the measures that have to be taken to scale up the chemical recycling of plastic packaging materials in the Netherlands in such a way that it contributes to the closing of the plastic chain.

In this study, we employ a number of basic principles:

- We focus specifically on the chemical recycling of *plastic packaging materials*, not on the chemical recycling of other waste streams[3]*;*
- We talk of chemical recycling when the output of the recycling process *is reused as a raw material by the manufacturing industry*[4], instead of being used as fuel, and

[2] Conclusion of the Netherlands Institute for Sustainable Packaging's Plastic Chain Project that was published in August of 2017.

[3] Some chemical recycling techniques can also be used to recycle plastic waste that does not come from packaging materials. Whenever measures affect these other waste streams, they are mentioned in chapter 1.3.

[4] In accordance with the definition of the National Waste Management Plan (LAP3), see definitions in chapter 3.1.

- We examine the opportunities that chemical recycling currently offers *when used in addition to the mechanical recycling of plastic packaging materials*, not as a replacement of mechanical recycling[5].

1.2 State of affairs

The development of chemical recycling techniques for plastic packaging materials has been going on for quite a while. A number of companies are researching chemical recycling processes in the form of pilot programmes. Based on the available input streams and sales markets for the output streams, cooperative alliances in the chain are being explored in order to apply these processes at a larger (industrial) scale. Given the current market developments and concrete initiatives in the form of pilot programmes, the realisation of the chemical recycling of plastic packaging materials at an industrial scale appears to be an ongoing process in the Netherlands at the moment and in the years to come.

Chemical recycling makes it possible to separate different types of plastic in a single product or packaging or to separate plastic from other (raw) materials (for example through solvolysis). Chemical recycling techniques vary from the breaking down of plastic packaging materials into their smallest chemical building blocks (gasification) to the breaking down of the material into its intermediate molecular stages from the plastic production chain (depolymerisation, pyrolysis). Among other things, these various techniques offer a solution for the declining quality of the polymer chains after each cycle of mechanical recycling. Depending on the technique being used, chemical recycling can be used to:

- Make the (raw) material suitable once more for food-grade applications; this is essential for major producers that have drawn up ambitions regarding the use of recycled plastics in their packaging materials, such as Unilever, P&G, Coca-Cola and Mars;
- Process relatively complex waste streams made up of various materials and adherent moisture and contaminants;
- Deal with troublesome contaminants or impurities (for example additives, odours and colours) in pure plastic streams;
- Create new materials, raw materials or building blocks for raw materials that can be used in a flexible manner with large sales markets and a wide range of possible applications.

[5] In this analysis, we examine the streams available in the current situation, where chemical recycling is used in addition to existing mechanical recycling methods. In the future, chemical recycling techniques may replace mechanical recycling techniques through innovation and market effects, for example due to a growing demand for food-grade or high-quality recycled raw materials.

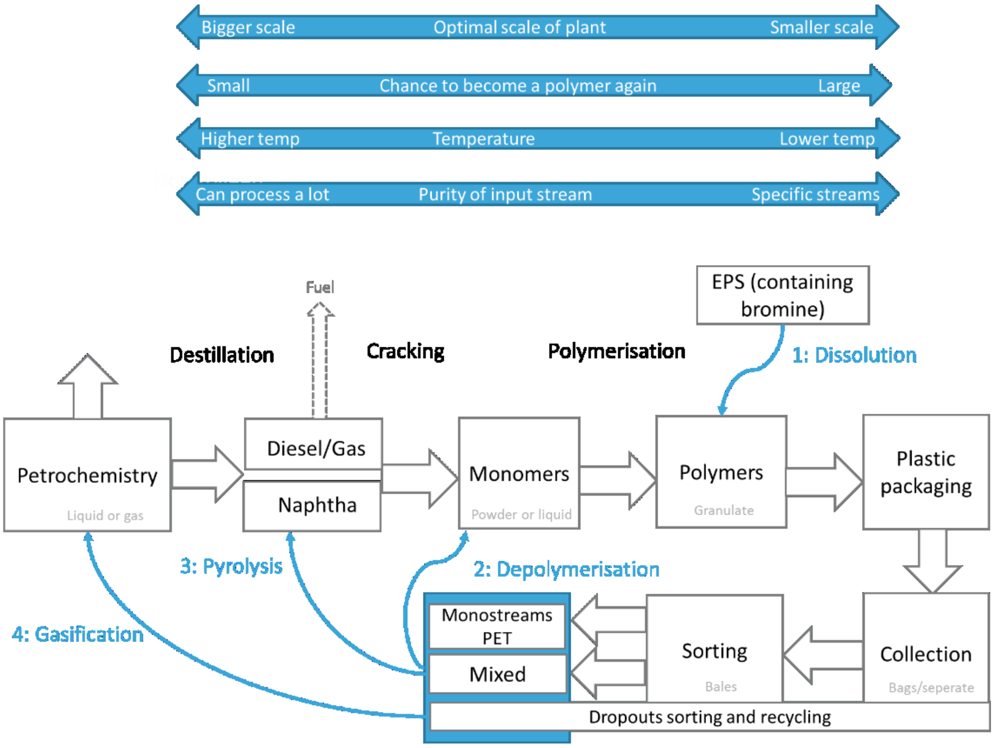

Image 1: A schematic overview of four chemical recycling techniques.

Scaling up the chemical recycling of plastics is nothing new. In recent years, various initiatives have been launched in the Netherlands regarding the chemical recycling of for example plastic packaging materials:

- Ioniqa (depolymerisation): breaks down PET packaging waste into pure raw materials from which colours and other contaminants are removed. Capacity to be realised in 2019: an output of 9 kt of BHET[6].
- Waste-to-Chemicals (gasification): Air Liquide, AkzoNobel Specialty Chemicals, Enerkem and the Port of Rotterdam want to build a facility to turn carbonaceous waste into methanol. In addition to plastic packaging waste, this facility will also process biomass, diapers, paper, etcetera. Capacity: an output of circa 200 kt (methanol).
- Bin2Barrel (pyrolysis): processes, among other things, plastic packaging waste streams that are difficult or impossible to recycle with mechanical techniques and which would otherwise end up in a waste-to-energy plant. It turns these streams into fuel and chemicals. Capacity: an output of 24 kt (fuels).
- Synbra (solvolysis): has set up a pilot facility that turns EPS into, among other things, PS. Capacity of the pilot facility: 3 kt of PS.
- Cumapol (depolymerisation): is working on a pilot facility for the recycling of PET waste, for example from packaging materials. Capacity after a successful pilot process: an output of 25 kt of BHET/PET.

This list is by no means comprehensive. There are other less-prominent initiatives regarding the use of chemical recycling in the Netherlands. These initiatives vary in terms of the processes they utilise and

[6] Intermediate product in the production chain of PET.

can contribute to the further development of the Netherlands' leading position and knowledge position in the field of the chemical recycling of plastic packaging materials.

1.3 Six steps with measures for upscaling

In order to apply the existing techniques for the chemical recycling of plastic packaging materials on an industrial scale, a system change is needed. That means that measures must be taken in every step of the plastic chain. We identify six steps that are needed at various places along the plastic chain. The image below provides a schematic overview of these steps. Steps 1 and 2 can be implemented at the same time. Next, steps 3 to 6 are needed, which can also be implemented together. These six steps are described in more detail below, along with the measures they require and the stakeholders that are involved.

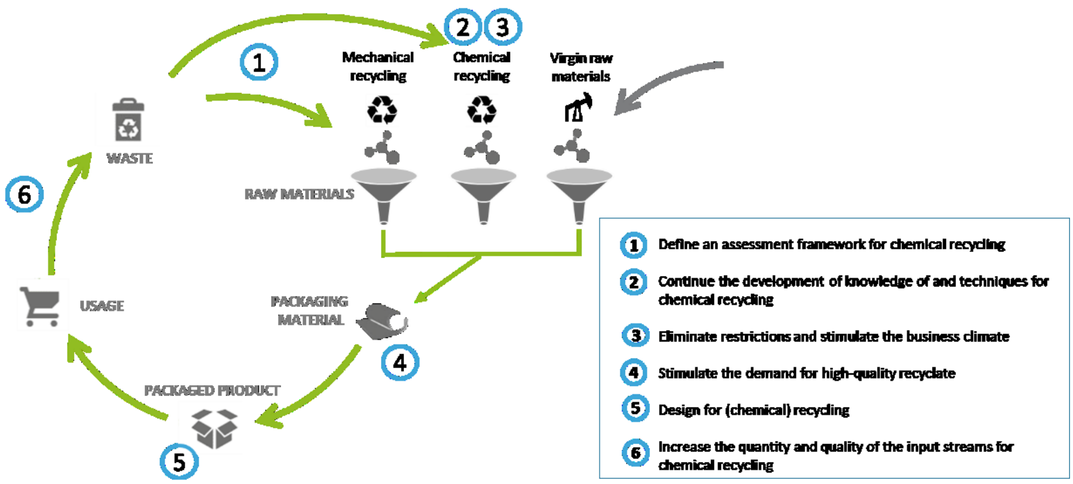

Image 2: Chain steps and associated measures in order to scale up the chemical recycling of plastic packaging materials.

Step 1: Define an assessment framework for chemical recycling

During the interviews that were held for the purposes of this analysis, it became clear that various principles and definitions of chemical recycling are being used. In order to realise the sector-wide upscaling of the chemical recycling of plastic packaging materials, it is essential that all stakeholders employ the same shared principles. To that end, a shared assessment framework can help to determine whether a certain development contributes to the jointly defined target.

Questions that are answered in the assessment framework for the upscaling of chemical recycling in the Netherlands[7]:

- What definition of chemical recycling is being used?
  (For example: when the output of chemical recycling is used by the manufacturing industry, when the recycling process produces raw materials for similar applications, when the output is turned into raw materials or fuel, etcetera).

[7] For the purposes of this analysis, we have defined principles that answer the questions in the assessment framework, see paragraph 1.1.

- What is the target that parties strive towards?
  (For example: recycling plastic packaging materials that are currently not being recycled using mechanical techniques, reducing CO_2 emission levels, producing an output of 250 kt of chemically recycled material by the year 2030, etcetera).
- Which input streams are used for chemical recycling?
  (For example: all streams of plastic packaging waste that are currently not being recycled using mechanical techniques, as many waste streams as possible in order to realise the targeted output or reduction of CO_2 emission levels, etcetera).
- How is chemical recycling used in relation to mechanical recycling?
  (For example: chemical recycling is only used for plastic waste streams that cannot be processed with mechanical recycling techniques, chemical recycling is used to increase the quality of low-quality streams and mechanical recycling is used to process high-quality streams, the free market decides which recycling technique is most profitable for which plastic waste stream, etcetera).

To ensure that this assessment framework is actively used, it is necessary for chain parties to become organised. This will create a platform in which joint initiatives can be implemented. Furthermore, the platform is used to define the assessment framework and apply it whenever considerations have to be made about specific joint measures and (incentive) measures that transcend individual corporate interests. The assessment framework can help initiate the transition and it can be updated as the transition is ongoing.

Define an assessment framework for chemical recycling		
Measure	**Chain party**	**Motivation**
Establish a work group for the chemical recycling of plastics.	Chemical recycling initiatives, collectors/sorters, recyclers, the national government, packaging companies	Develop knowledge, implement measures, secure funding.
Draw up an assessment framework for chemical recycling.	Chemical recycling initiatives, collectors/sorters, recyclers, the national government, the Packaging Waste Fund, packaging companies	Develop individual targets for stakeholders, foundation for the national government's policy framework and joint targets for the work group.
Explore scenarios in which possible combinations of various mechanical and chemical recycling techniques are used. The KIDV can provide relevant information.	VNO-NCW, the national government, chemical recycling initiatives, recyclers, packaging companies	Gain insight into the available input streams, environmental impact and associated costs of various scenarios.

Step 2: Continue the development of knowledge of and techniques for chemical recycling
Scaling up chemical recycling requires knowledge on the part of stakeholders about the (im)possibilities of the various processes. Establishing a connection between the chemical and waste sectors requires knowledge of both worlds. The table below outlines which technical challenges are yet to be resolved and which chain parties are responsible for doing so.

Continue the development of knowledge of and techniques for chemical recycling		
Measure	**Chain party**	**Motivation**
Defining shared knowledge questions, which create a foundation for stakeholders' joint research projects.	Chemical recycling initiatives, collectors/sorters, recyclers, the national government, packaging companies	Fill in knowledge gaps and spread knowledge among stakeholders (equal knowledge level).
Research which technological developments should be stimulated in the Netherlands, based on what is already being done in neighbouring countries.	Chemical industry, the national government	Expand the Netherlands' knowledge position pertaining to chemical recycling.
Research the technical (im)possibilities and current restrictions for chemical recycling of the sorting and recycle losses.	Chemical recycling initiatives, sorters, recyclers	Expand the potential feedstock and increase the recycling rate.
Research the logistic and economic structures needed for the chemical recycling of waste streams that are difficult or impossible to recycle mechanically.	Chemical recycling initiatives, sorters, Packaging Waste Fund	Expand the potential feedstock and increase the recycling rate.
Research where legislation and incentive measures stimulate the chemical conversion into fuel, instead of utilising the output of chemical recycling as raw material.	The national government	Stimulate chemical recycling processes that produce new raw materials.
Explore opportunities to use solvolysis to separate multi-layers (tying into the developments within CeFlex[8]) or remove additives.	Producers of packaging materials, packaging companies and chemical recycling initiatives	Multi-layer packaging materials are hard to recycle mechanically, yet they offer excellent functionalities for food packaging.
Research the conditions for private investors to invest in the upscaling of chemical recycling processes.	Packaging companies, chemical recycling initiatives or the chemical industry, the	Secure funding for the upscaling of chemical recycling.

[8] CeFlex is a project in which chain parties collaborate at the European level to optimise flexible packaging materials from design to recycling. One of the CeFlex projects involves research into multi-layer packaging materials that are easier to recycle, as well as recycling methods that are better able to process existing multi-layer packaging materials.

	national government (Invest-NL)	
Research which (traces of) contents of packaging materials may disrupt chemical recycling processes.	Chemical recycling initiatives	Input for guidelines for design for chemical recycling.

Step 3: Eliminate restrictions and stimulate the business climate
At the moment, parties that wish to scale up their use of chemical recycling techniques encounter financial, technical, legal or policy-related restrictions. These restrictions must be clearly identified, so they can be eliminated if possible. Furthermore, it is important to determine what must be done in order to create an attractive business climate for chemical recycling companies.

Eliminate restrictions and stimulate the business climate		
Measure	**Chain party**	**Motivation**
Identify the conditions for private investors to invest in the upscaling of chemical recycling.	Packaging companies, chemical recycling initiatives or the chemical industry, the national government (Invest-NL)	Secure funding for the upscaling of chemical recycling.
Invest in an attractive business climate for the chemical industry.	National, provincial and municipal governments	Attract chemical industry that contributes to circular ambitions.
Develop smart cooperation structures between the chemical industry and the waste management sector in light of investment costs and the logistical costs of organising feedstock (for example plastic from recycle losses and other waste streams).	Packaging Waste Fund, collectors, sorters, chemical recycling initiatives, waste-to-energy plants, chemical industry	Create opportunities to save on investment costs.
Continue providing incentive grant(s) for promising initiatives based on their performance in terms of the preservation of raw materials and the realisation of environmental benefits.	Ministries of Economic Affairs & Climate Policy and Infrastructure & Water Management	European climate targets and Transition Agendas/Raw Materials Agreement.
Create room for the development of (specific) chemical recycling techniques for plastic packaging materials in the event of possible changes to agreements in the Framework Agreement for Packaging (2013-2022) following the evaluation.	Framework Agreement parties	Increase the percentage of recycled plastic packaging materials.

Set up a compensation system for the Framework Agreement for Packaging (2013-2022) and Execution and Monitoring Protocol to create room for the sale of sorted plastic packaging waste to chemical recyclers.	Packaging Waste Fund	Increase the percentage of recycled plastic packaging materials.
Draw up policies to (ultimately) use all output of chemical recycling processes as raw material (instead of fuel).	European Commission, the national government	Stimulate the preservation of raw materials.
Set up a transition programme or policy to facilitate the temporary use of chemical recycling output as fuel to stimulate business cases, if necessary.	The national government	Scale up chemical recycling in the Netherlands.
Stimulate the processing of the current stream of mixed plastics and/or plastic packaging materials in residue with chemical recycling in the Netherlands.	Chemical recycling initiatives, the national government	Process plastic packaging materials from Dutch waste streams in the Netherlands, rather than abroad.

Step 4: Stimulate the demand for high-quality recyclate
Increasing the demand for high-quality materials and raw materials and thereby competing with virgin raw materials is paramount for the upscaling of chemical recycling. It is also essential that chemical recycling can offer supply security for materials or raw materials that are similar to fossil resources in terms of properties and price.

Stimulate the demand for high-quality recyclate		
Measure	**Chain party**	**Motivation**
Implement policy measures that increase the demand for recycled plastics and raw materials and thereby stimulate chemical recycling (for example CO_2 tax for virgin plastics).	The national government, Europe	Realise the ambitions from the Transition Agenda for Plastics and manufacturing industry regarding the preservation of raw materials.
Explore opportunities to designate the output of solvolysis and depolymerisation as recyclate suitable for food-grade applications.	The national government in accordance with EFSA	Increase the possible applications of and demand for recycled plastics.
Identify the demand (and therefore the sales market) for recycled raw materials for packaging materials and translate that into output for mechanical and chemical recycling.	Packaging companies, chemical recycling initiatives, recyclers	Supply security for recycled raw materials.

Step 5: Design for (chemical) recycling

It is important to prevent the use of interferents for (mechanical and) chemical recycling in packaging materials. It is therefore important to identify these interferents and develop "design for chemical recycling" guidelines to reduce the use of these substances.

Design for (chemical) recycling		
Measure	**Chain party**	**Motivation**
Develop "design for chemical recycling" guidelines.	Chemical recycling initiatives and packaging companies	Facilitate the distribution of knowledge about "design for chemical recycling" for packaging materials.
Reduce the use of interferents in packaging materials that are chemically recycled.	Chemical recycling initiatives, packaging companies and sorters	Realise a technical improvement of the chemical recycling of packaging materials.

Step 6: Increase the quantity and quality of the input streams for chemical recycling

In order to realise a sound business case, the supply security of input streams is essential. It is therefore important that the sufficient quantity and quality of the input streams for chemical recycling are guaranteed. The input of plastic packaging materials must be seen from the right perspective: depending on the chemical recycling process used, plastic packaging materials only make up part of the total feedstock.

Increase the quantity and quality of the input streams for chemical recycling		
Measure	**Chain party**	**Motivation**
Concretise and, if necessary in order to achieve a beneficial scale, organise import opportunities (for example PET stream), for example by talking with foreign governments about classifying (certain forms of) chemical recycling as a form of recycling at the EU level.	The national government	Accomplish the amount of plastic packaging materials to realise the desired scale, generate a recycle market in the Netherlands.
Organise the import of plastic packaging streams that are similar to the Dutch streams, for example by talking with foreign manufacturer responsibility organisations (Fost Plus, DSD, etcetera).	Chemical recycling initiatives, recyclers and the Packaging Waste Fund	Realise the desired scale, generate a recycle market in the Netherlands.
Organise and offer supply security for the input streams of chemical recycling companies (particularly solvolysis and depolymerisation).	Chemical recycling initiatives and sorters	This applies to all input streams. Realise a minimum volume of PET waste for investment in a

		recycling facility in the Netherlands.
Optimise the collection and sorting of plastic packaging materials from households and the office, retail and services sector.	Municipalities, the national government	Realise the separation targets for waste from households and the office, retail and services sector and ultimately contribute to recycling targets.
Coordinate the streams of plastic packaging materials from the office, retail and services sector that are not suitable for mechanical recycling – and therefore available for chemical recycling – and the feedstock requirements of specific chemical recycling techniques, for example with specific collection and/or sorting processes.	The national government, collectors, chemical recycling initiatives	Supply security of the feedstock.
Research possibilities to expand manufacturer responsibility for other plastic products.	The national government	Increase the (separate) collection of plastic products, in addition to packaging materials.
Research opportunities to chemically recycle plastic from electric and electronic equipment. The introduction of Weeelabex[9] regulations will result in more collected plastic.	Chemical recycling initiatives and buyers of plastic recyclate from electric and electronic equipment	High-quality applications for recycled (hard) plastics from electric and electronic equipment.

[9] Waste Electric and Electronic Equipment LABel of Excellence (Weeelabex) is an initiative developed by European collection organisations for electric and electronic equipment, including Wecycle, who are united in the WEEE Forum.

2 Summary of findings and conclusions pertaining to the chemical recycling of plastic packaging materials

The analysis of the chemical recycling of plastic packaging materials (part 2 of this report) forms the foundation for the conclusions and measures. The analysis provides an overview of the opportunities that chemical recycling presents for the Netherlands, as well as an economic and environmental analysis of the various chemical recycling techniques. The findings and conclusions are based on the static representations of the performances of the various processes, based on four processes that were evaluated at a pilot scale. The information regarding these processes is not based on their performance at an industrial scale and includes a relatively large degree of uncertainty.

2.1 Chemical recycling alongside mechanical recycling

In the short term, chemical recycling can be used in addition to mechanical recycling to deal with the limitations and practical restrictions of mechanical recycling. For example, not all types of plastic are suitable for mechanical recycling. The input of a mechanical recycling process must possess a certain degree of purity in order to safeguard the quality of the recyclate. Plastic composites, laminates, paper stickers or labels and organic residue all impede the recycling process. Furthermore, the presence of (non-plastic) contaminants and certain types of films can cause the mechanical recycling equipment to jam. Lastly, odours are also a factor. At the moment, mechanically recycled plastic from packaging materials that have been collected via household waste collection systems or as industrial waste is often unsuitable for food-grade applications[10]. Plastic packaging materials can go through a limited number of recycling processes, because the quality of the material declines after each cycle. In order to retain the desired quality, it is currently necessary to add virgin plastic to the recyclate. In order to further close the plastic chain in the short term, measures must be taken to optimise mechanical recycling to allow more waste streams to be recycled mechanically and increase the quality of the recyclate. In the long run, chemical recycling techniques may replace mechanical recycling techniques due to market effects, for example due to a growing demand for recycled raw materials that can be used for food-grade or high-quality applications.

This study examines input streams that are difficult or impossible to recycle mechanically at a high-grade level. These streams are therefore potentially ideal for chemical recycling. In practice, chemical recycling processes can compete with mechanical recycling. The market can, or will, determine how mechanical and chemical recycling processes can coexist.

In order to further study the opportunities and possibilities of the chemical recycling of plastic packaging materials in the Netherlands, analyses were conducted of the economic viability, the environmental impact and the opportunities that chemical recycling presents for the Netherlands. Furthermore, the restrictions and opportunities of the chemical recycling of plastic packaging

[10] One of the guidelines of the EFSA – it must be possible to trace back at least 95% of the material in the recycling process to material that comes from the food industry – impedes the large-scale application of recycled plastics for plastic packaging materials for food products. The origins of packaging materials that are collected via comprehensive collection systems or subsequent separation are untraceable, with the exception of PET bottles from the deposit refund stream.

materials in terms of policies and regulations were examined. To do so, one modelled demonstration process has been examined in more detail for each of the four main chemical recycling techniques (solvolysis, depolymerisation, pyrolysis and gasification). Table 1 shows which input and output streams were used for each chemical recycling technique. In this analysis, we employ the principles as outlined in paragraph 1.1.

<table>
<tr><th></th><th></th><th colspan="3">Demonstration processes</th><th></th></tr>
<tr><th>Target and definition</th><th>Chemical recycling technique</th><th>Demonstration process</th><th>Input stream</th><th>Output stream</th><th>Characteristics</th></tr>
<tr><td rowspan="4">Target: chemical recycling of plastic packaging materials that are currently difficult or impossible to recycle mechanically

Definition of chemical recycling in accordance with the National Waste Management Plan 3: output is used as raw material for the manufacturing industry.</td><td>Solvolysis</td><td>Creasolv</td><td>EPS with brominated flame retardants (from the construction sector)</td><td>PS and Bromine</td><td rowspan="2">Strict requirements for the composition of the input stream

High-quality output, limited processing required to create plastic granulate comparable to virgin material and suitable for use in plastic (packaging materials)</td></tr>
<tr><td>Depolymerisation</td><td>PET glycolysis</td><td>PET trays</td><td>BHET[11]</td></tr>
<tr><td>Pyrolysis</td><td>Rapid low-temperature pyrolysis</td><td>Mixed plastics[12]</td><td>Naphtha, diesel and gas[13]</td><td rowspan="2">Heterogenous input required, more comprehensive than plastic packaging materials
For gasification, no more than 20% of the feedstock consists of plastic material

Output can be reused as raw material (for plastic). Doing so required additional processing steps.

Output can also be used as fuel (this is not classified as recycling according to the definition in the National Waste Management Plan 3)</td></tr>
<tr><td>Gasification</td><td>High-temperature gasification</td><td>Recycle losses</td><td>Syngas or methanol</td></tr>
</table>

Table 1: Points of attention for the four modelled demonstration processes for chemical recycling techniques.

[11] Intermediate product of the production of PET.
[12] Whenever this analysis makes mention of the stream of mixed plastics, this refers to plastic packaging materials that are not recyclable via a mono-stream. These materials end up in the sorted streams according to the specifications DKR 350 or DKR 352. At some point in the future (to be determined), these specifications will be replaced by the new sorting specification for the Mixed Polyolefins (MPO) material stream.
[13] The use of the diesel and gas as fuel falls outside the definition of chemical recycling used in this analysis (see definitions in chapter 3.1).

The analysis of the four demonstration processes for chemical recycling techniques for plastic packaging materials[14] results in the following points of attention:

- Each of the four techniques requires a different input stream and produces a different output. That means that these techniques cannot be compared to each other and are used in conjunction.
- The outputs of solvolysis and depolymerisation processes are close to plastic granulate. Their cycles are therefore shorter than those of pyrolysis and gasification processes.[15]
- Solvolysis and depolymerisation produce an output of pure polymers or monomers, comparable to virgin plastics. Both techniques have strict requirements for their input streams.
- For gasification, the input stream of plastic packaging materials forms only a small part of the feedstock of the recycling process: the majority of the input consists of other waste streams, alongside the stream of plastic packaging materials. The composition of the feedstock depends, among other things, on the differences in energetic value of the input streams, the output of the process and the rates for the input streams. The other input streams that are processed along plastic packaging materials are highly relevant for the business case and the upscaling potential. In the case of pyrolysis, the feedstock mainly consists of plastics, but it may also contain a limited percentage of non-plastic material.
- Gasification and pyrolysis are less vulnerable to fluctuations in the composition of the feedstock.
- Part of the outputs of pyrolysis and gasification processes can also be used as fuel. In that case, these processes fall outside the current National Waste Management Plan 3 definition of chemical recycling.

2.2 Key findings

To develop the conclusions and measures for upscaling, economic and environmental analyses were conducted for four demonstration processes for the chemical recycling of plastic packaging materials. Furthermore, the opportunities that the upscaling of the chemical recycling of plastic packaging materials creates in the Netherlands and the restrictions and opportunities in terms of regulations and policies were examined. The key findings of these analyses are the following:

Opportunities presented by chemical recycling techniques (the detailed findings are outlined in chapter 3.1)

1. The chemical recycling of plastic packaging materials offers, among other things, a solution for the declining quality of the polymer chains after each recycling process. Chemical recycling can be used to process relatively complex streams and remove contaminants and additives from the plastic stream.
2. Realising the ambition from the Transition Agenda for Plastics in the Netherlands creates opportunities for the Netherlands to expand its leading position in the field of collecting, sorting and recycling plastic packaging materials into a leading position in the field of chemical recycling.
3. Based on this ambition, a capacity of 250 kt output of chemical recycling, based on an average capacity of 50 kt input per recycling facility, allows for the realisation of at least five recycling facilities in the Netherlands. This will lead to economic benefits in the form of new jobs and stimulate the development of knowledge of chemical recycling.

[14] See chapter 5 of Part 2 of this analysis.
[15] These processes break down the plastic packaging materials into their chemical building blocks. Further processing steps are then required to turn the outputs of syngas and/or naphtha into raw materials (for plastic).

4. Pyrolysis and gasification are the chemical recycling techniques that can be used in the short term to process plastic streams that are currently difficult or impossible to recycle mechanically (mixed plastics and plastic packaging materials from the recycling losses). These processes can therefore contribute to the recycling of plastic packaging materials. The output of pyrolysis and gasification consists of fuels and/or chemicals. These outputs can be reused as raw materials and therefore contribute to a circular economy. The output can also be used as fuel. In that case, the process is not classified as chemical recycling according to the current definition in the National Waste Management Plan; instead, we classify this as chemical conversion.
5. Solvolysis can offer added value in the long run for the recycling of niche plastic packaging materials. One example is that the layers of PP and PE in multi-layer packaging materials can be separated from each other or from other materials (aluminium). At the moment, this process is not economically viable and these packaging materials are processed via mechanical recycling. However, current mechanical recycling methods limit the number of possible applications of the material, because multi-layer packaging materials end up in the stream of mixed plastics or are eliminated during sorting or recycling and then incinerated.
6. Depolymerisation is a promising technique that can be used for PET packaging materials (including PET trays and DKR 328-1), which are currently mostly recycled with mechanical techniques. The added value of depolymerisation over mechanical recycling lies in the fact that rPET can be used for food-grade applications after depolymerisation, since any odours, colours and additives are removed from the polymers.
7. It is important that the upscaling of the chemical recycling of plastic packaging materials involves more than the recycler's interests alone (where the financial value mostly ends up). Social interests and the non-financial interests of stakeholders are just as important, for example supply security and risk assessments made by producers of packaged products (the assessment framework for the upscaling of chemical recycling in the Netherlands outlined in step 1 of Part 1 of this report may play a part in this).

Environmental impact (the detailed findings are outlined in chapter 5)

8. The environmental impact of the demonstration processes that were analysed is mostly determined by the energy consumption and excipients, the replacement of virgin raw materials and the emission of greenhouse gases.
9. The reduction of CO_2 emission levels (compared to incineration) in the solvolysis and depolymerisation chains is comparable to that of mechanical recycling. The reduction in the pyrolysis and gasification chains is circa half of that, compared to incineration in a waste-to-energy facility.
10. The depolymerisation of PET trays has an environmental impact that is comparable to that of the mechanical recycling of PET into material of food-grade quality[16]. The positive environmental impact mostly stems from the replacement of virgin PET.
11. The solvolysis of EPS with brominated flame retardants from the construction sector[17] offers environmental benefits that are comparable to the mechanical recycling of this stream, compared to incineration. Solvolysis offers the same options as depolymerisation when it comes to eliminating other substances or materials from the plastic material.

[16] In terms of environmental impact, magnetic depolymerisation of PET scores worse than the mechanical recycling of PET, the technique used as a reference in this environmental analysis. The steps required to make PET trays suitable for food-grade applications after mechanical recycling ultimately result in comparable environmental impacts for mechanical and chemical recycling, both compared to incineration.

[17] Although this input stream is not a packaging stream, it was used in the modelled demonstration process for solvolysis, because it is an available plastic stream that is currently already being recycled with chemical techniques at a pilot scale.

12. The environmental impacts of the depolymerisation of PET and the pyrolysis of the stream of mixed plastics are comparable to that of the mechanical recycling of these streams of plastic packaging waste. The pyrolysis or gasification of recycling losses offer environmental benefits compared to the current processing technique, since the plastic is not incinerated and the output replaces a fuel or chemicals.
13. The pyrolysis of the stream of mixed plastics has an environmental impact that is comparable to that of mechanical recycling of the mixed plastics. However, the mechanical recycling of the stream of mixed plastics results in a lower CO_2 reduction per ton, compared to the mechanical recycling of mono-streams. In other words, the standard for equal performance in terms of environmental impact is lower. Depending on the type of pyrolysis process being used, the output consists of (a combination of) fuel and/or chemicals, including naphtha. Naphtha is a valuable chemical product that can be used for the production of new plastics.
14. The gasification of plastic packaging materials from sorting and recycling losses or mixed plastics has an environmental impact that is comparable to that of the mechanical recycling of the stream of mixed plastics. The output of gasification is syngas, which can be used as fuel or processed into methanol. This, in turn, can be used as a building block for raw materials or as fuel.

Economic viability (the detailed findings are outlined in chapter 5)

15. Setting up chemical recycling installations is a capital-intensive endeavour. The production costs make up the bulk of the costs. These are mainly determined by the operational costs, for example energy and maintenance.
16. The operational costs of the demonstration processes for solvolysis and depolymerisation are mainly determined by the energy costs.
17. The operational costs of pyrolysis are strongly influenced by the pre-processing of the input stream of plastic packaging materials; incinerating the off-gas that is produced during the pyrolysis process provides the process energy required for the pyrolysis, which keeps the energy costs down.
18. The operational costs of the gasification process are strongly influenced by the costs of oxygen and hydrogen. These industrial gases are needed for the gasification into syngas and the subsequent reaction to produce methanol.
19. The production costs of all demonstration processes that were examined for this analysis depend on the feedstock price, which fluctuates along with the demand and supply market.
20. Furthermore, the potential gross profit of the demonstration processes is partly determined by the price of the output, which depends on the plastics market and the oil price.
21. For the four modelled demonstration processes, the feedstock price and scale of the process have the biggest impact on the production costs: a low feedstock price and upscaling offer beneficial effects. The oil price has a smaller impact on the production costs of these processes.
22. For gasification, the scale of the process has a significant impact on the production costs: it is a decisive factor for a positive business case.
23. Two stimulating factors that can have a positive impact on the businesses cases are: investments from companies that produce packaged products and want supply security to produce (recycled) plastic packaging materials and incentive measures from the government to stimulate recycling.
24. The supply security of the input streams of plastic packaging waste is essential in order to safeguard both the quality and the quantity of the material.
25. Solvolysis and depolymerisation processes face competition from mechanical recycling. It is essential to identify feedstock streams that are difficult to recycle mechanically (for example due to the presence of additives): these are promising streams for chemical recycling.
26. Pyrolysis and gasification can process more comprehensive feedstock streams (for example household waste, biogenic streams) to which plastic packaging materials can be added.

27. The quality of the feedstock is essential, because a low quality results in a lower product yield and/or higher pre-processing costs for the feedstock. This directly affects the profit margins of the recycling process. Agreements made between the chemical recycler and the waste collectors or sorters should result in input with the required quality.
28. For the demonstration processes that were examined in this study, positive business cases (i.e. earning a gross profit) are possible when:
    a. Favourable technical parameters are employed (for example scale);
    b. The operational costs are managed or reduced (for example the costs of the required excipients);
    c. Incentive measures are utilised (for example subsidies or loans with favourable terms); and
    d. The existing system in which the collecting and sorting of plastic packaging waste is reimbursed continues to exist.
29. Targets or ambitions to facilitate the higher-quality recycling of laminates can contribute to the realisation of solvolysis for plastic packaging materials at the pilot and industrial scale.
30. When it comes to scaling up depolymerisation processes for plastic packaging materials, the involvement of producers and importers of packaged products is wanted. They can offer supply security for input streams suitable for depolymerisation and guarantee the sale of the recycled raw materials.

Ambition Transition Agenda for Plastics (clarification provided in chapter 6)

31. The ambition from the Transition Agenda for Plastics to realise an annual output of 250 kt for the chemical recycling of plastics (both packaging materials and plastic products) can be attained by using only the stream of plastic packaging materials that are currently not recycled mechanically as input. It is therefore necessary to optimise existing collection systems or import plastic packaging materials from neighbouring countries. Otherwise, plastic streams that consist of non-packaging materials are also needed as feedstock in order to realise this ambition.
32. Other plastic streams that could potentially be used are:
    - Plastic packaging waste from businesses that is currently not collected separately. A large part of this stream, particularly the plastic packaging waste from the office, retail and services sector, could for example be collected separately or sorted, divided by types of plastic that meet the input requirements for chemical recycling.
    - Plastic from the construction or automotive sectors, for example brominated EPS, already forms a promising stream that is suitable for processing with solvolysis. It is included in the environmental and economic analyses in this report.
    - Imported plastic packaging waste.

Restrictions and opportunities in terms of regulations (detailed findings are outlined in chapter 6)

33. Current regulations are partially designed to eventually facilitate chemical recycling. At the moment, a distinction is made between chemical recycling processes and processes that produce energy or fuel. A process is classified as a recycling process when its output is reused as a raw material for the manufacturing industry[18]. The chemical processes whose output is used as energy or fuel are therefore not classified as recycling.
34. In the government-wide Circular Economy programme and in the implementation of various subsidy schemes, the national government outlines its policy ambitions regarding the stimulation of the chemical recycling of plastics. The National Waste Management Plan 3 also lets chemical

[18] The definition of chemical recycling used in LAP3.

recycling contribute to the recycling targets, as long as the output of the processes is used as a raw material for the manufacturing industry[19].

35. Incentive measures for biofuels can affect whether the output of pyrolysis and gasification processes is used as a raw material or as fuel. Depending on the composition of the input streams (which largely consist of for example biomass or residual streams, in addition to a percentage of plastic packaging waste), the (incentive) policy for biofuels can stimulate the use of the output as fuel. This results in competition between reusing the material as raw material (via waste-to-chemicals) or processing it into fuel (waste-to-fuels).
36. The current system of refunds and sorting specifications for plastic packaging materials does not incentivise municipal governments, collectors and sorters to utilise chemical recycling, because collection and sorting fees do not apply to plastic packaging materials that are processed by a chemical recycler.

2.3 Conclusions

1. From a technical perspective, it is possible to utilise chemical recycling to produce recycled plastic or new raw materials with a quality similar to that of virgin materials.
2. Producers' demand for recycled plastic with a quality similar to that of virgin plastics is growing. This may currently or eventually lead to the further development and upscaling of chemical recycling processes for plastic packaging materials.
3. Commitment to or investments in chemical recycling installations by packaging companies or players in the raw materials industry are essential for the implementation of chemical recycling[20]. By doing so, producers create supply security for recycled plastics that meet their requirements and they can meet their sustainability ambitions. Collaboration in the plastic chain results in the better coordination of supply and demand.
4. However, chemical recycling is not a one-size-fits-all process with which all types of plastic packaging materials can be recycled into recyclate with a quality similar to that of virgin material. Chemical recycling is a collective term for specific processes, each with its own requirements for the input stream of plastic packaging materials. For example, depolymerisation processes require a homogenous input stream of only polycondensates. Gasification processes can handle a more heterogenous feedstock, where the plastic stream only makes up part of the total feedstock. For pyrolysis, the feedstock mainly consists of plastics, but it may also contain a small percentage of non-plastic materials. Furthermore, the outputs of the various chemical recycling techniques not only consist of raw materials for plastic packaging materials, but also of raw materials that can be used by the chemical industry or as fuel.
5. The chemical recycling of plastic packaging materials fits within a circular economy when the output of the recycling process is used to produce new raw materials. Regulations must stimulate using the output of pyrolysis and gasification processes (fuels and chemicals) as raw materials, thereby contributing to the closing of the raw material chains.
6. The business cases that were developed for four demonstration processes of the chemical recycling of plastic packaging materials show varying results. There are significant differences between the processes in terms of their investment costs, uncertainties and operation costs per ton of output.

[19] The definition of chemical recycling used in LAP3.

[20] Various cooperative alliances between producers of plastic products or packaging materials and (chemical) recycling organisations were recently launched. In early April of 2018, Unilever announced its collaboration with the start-up Ioniqa and PET producer Indorama Ventures. The companies are working together to develop a new technology with which to turn PET waste into pure plastic raw materials that can be used for the production of packaging materials for food.

7. The costs and gross profits of the processes depend mainly on the scale of the process, the costs of the feedstock and the sales price of the products. These variables ultimately determine the processes' costs and profits.
8. Two stimulating factors that may have a positive impact on the business cases of chemical recyclers are investments from companies that produce packaged products and want supply security for (recycled) plastics and incentive measures from the government to stimulate recycling.
9. The environmental impacts of the depolymerisation of PET and the pyrolysis of the stream of mixed plastics are comparable to that of the mechanical recycling of these streams of plastic packaging waste. The pyrolysis or gasification of recycling losses offer environmental benefits compared to the current processing technique, since the material is not incinerated and the output replaces a fuel or chemicals.
10. Per kilogram of plastic packaging waste, the environmental benefits of depolymerisation and solvolysis are comparable to those of the mechanical recycling of mono-streams of plastic packaging materials.
11. The current system of refunds and sorting specifications for plastic packaging materials lacks an incentive for Framework Agreement parties[21], municipalities and sorters to strive towards developing qualitatively better recycling methods. At the system level, the plastic packaging chain would benefit from more and better recycling, which would allow for higher-grade applications.
12. Current laws and regulations present opportunities for the implementation of chemical recycling. The distinction between chemical recycling processes that produce raw materials and those whose output is used as fuel must continue to be made. Furthermore, a distinction could be made by looking at the amount of CO_2 reduction per ton of processed plastic packaging waste, compared to incineration of the plastics.
13. Even when chemical recycling is utilised at an industrial scale for the processing of Dutch plastic packaging waste, it is still necessary to keep working on "design for recycling," collaboration in the packaging chain and effective collection systems.
14. In order to realise and set up the chemical recycling of plastic packaging materials, collaboration in the chain is needed:
    - To implement chemical recycling, the right composition and supply security of the feedstock are important. Collaboration between the back (recycler) and front (producer) of the packaging chain is therefore essential;
    - Avoiding the use of interferents through the design of packaging materials. This requires collaboration between producers and importers of packaged products and recyclers;
    - Processing sorting and recycling losses requires logistical solutions that involve collaboration between sorters and recyclers;
    - Investments and incentive measures throughout the entire chain.

[21] The Ministry of Infrastructure and Water Management, the Association of Dutch Municipalities and the producers and importers that put packaged products on the market.

Part 2: Analysis of the chemical recycling of plastic packaging materials

3 The opportunities of the chemical recycling of plastic packaging materials for the Netherlands

To develop the conclusions and measures for the upscaling of the chemical recycling of plastic packaging materials, the opportunities for the Netherlands were evaluated and economic and environmental analyses were conducted. Furthermore, the restrictions and opportunities for the chemical recycling of plastic packaging materials in terms of regulations and policies were examined. The results of these analyses are described in this second part of the report.
This chapter covers the opportunities of the chemical recycling of plastic packaging materials for the Netherlands.

3.1 An overview of the opportunities for the Netherlands

The realisation of the chemical recycling of plastic packaging materials at an industrial scale is currently being substantiated in the Netherlands. This process will continue in the years to come. In some ways, the upscaling of chemical recycling creates opportunities for the Netherlands. In addition to realising its circular ambitions, the Netherlands can assume a leading role and a prominent knowledge position in the field of the chemical recycling of plastic packaging materials. Finally, the continued development of for example the existing initiatives outlined in chapter 1.2 also creates economic opportunities.

Various definitions of (chemical) recycling are used in agreements and regulations pertaining to packaging materials and in waste management policies. The definitions differ in the applications of the output product.

1. Chemical recycling in the recycling target of the VANG policy: volumes that have been recycled and are reused as <u>the original materials</u> count as recycling and contribute to the realisation of the VANG targets.
2. Chemical recycling in the National Waste Management Plan 3: The chemical process is only classified as a form of recycling when it is designed to <u>produce raw materials</u> for the manufacturing industry, not when the output is used as fuel.
3. Recycling used in the refund system for plastic packaging materials: Volumes of plastic packaging materials that are <u>sold to a certified recycler</u>.
4. Decision packaging management: The reprocessing of waste materials in a production process for the <u>original purpose or for other purposes</u>, including organic recycling but excluding the recovery of energy.

In the “Chemical recycling of plastic packaging materials: analysis and opportunities for upscaling” report, we employ the definition formulated in the National Waste Management Plan 3.

A leading position in the field of chemical recycling

The Transition Agenda for Plastics includes the ambition to realise 10% of the output of all recycling processes with the chemical recycling of plastics by the year 2030. That requires a combined output of

250 kt for all chemical recycling techniques. Realising this ambition in the Netherlands creates opportunities for the Netherlands to expand its leading position in the field of waste collection and mechanical recycling into a leading position in the field of chemical recycling.

In this analysis, we employ the principle that only those streams that are currently difficult or impossible to recycle with mechanical techniques are available for chemical recycling. If we want to increase the input streams of plastic packaging materials that are suitable for chemical recycling, for example to increase the supply security of the feedstock, we would have to optimise existing collection systems or import plastic packaging waste from neighbouring countries. Think of for example the sorted stream of mixed plastics that is largely processed in Germany at the moment[22]. It is also possible to import waste material from other countries. In addition to plastic packaging waste from households, there are other promising streams: plastic packaging waste from the office, retail and services sector, plastic packaging materials from the industrial waste stream that are not being recycled at the moment[23] or plastic products, for example EPS from the construction sector, plastics from the automotive sector or from discarded electric and electronic equipment (WEEE stream).

Economic opportunities

Based on the ambition from the Transition Agenda for Plastics, a capacity of 250 kt output for chemical recycling, based on an average capacity of 50 kt input per recycling facility, allows for the realisation of five recycling facilities in the Netherlands. This is expected to require a significant investment that is estimated at circa €285 million[24]. At the same time, this investment will create circa 225 direct jobs in the recycle facilities themselves.[25] Furthermore, the development of knowledge (and jobs in the knowledge sector) will also receive an impulse.

Important conditions are the cost effectiveness of chemical recycling and the environmental benefits of the various techniques. An incentive programme from the Ministry of Economic Affairs and Climate Policy will soon launch. It is intended to support pilot projects in the field of chemical recycling. The goals of this programme are to reduce the cost price of chemical recycling, improve its ability to compete with the incineration of waste streams, realise more CO_2 reduction and reduce the loss of raw materials (compared to incineration). Furthermore, at least 70% of the output of chemical recycling must be reused for the production of new products[26].

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[22] Increased reuse targets in Germany may eventually result in a larger stream of mixed plastics from German waste. This will push out the stream of mixed plastics from the Netherlands that is currently being processed entirely in Germany.

[23] 55 to 60% of the plastic packaging waste from businesses is currently collected separately and then processed. The Chinese import ban mostly affects the stream of films from businesses. https://www.kidv.nl/7634/verslag-verdiep-bijeenk-kidv.pdf?ch=DEF

[24] Assumption: an investment of € 860.000 per kt of capacity to be realised. When 330 kt of plastic feedstock results in 250 kt output (80% efficiency/yield).

[25] Assumption: 0.9 FTE per kt of realised capacity

[26] Document: Programme lines BBEGR Innovation 2018, programme line 3: https://www.rvo.nl/subsidies-regelingen/subsidies-energie-innovatie-topsector-energie/biobased-economy-groen-gas-en-recycling.

4 Methods for the economic and environmental analysis of demonstration processes

This chapter provides an overview of the available input streams for chemical recycling and the methods used for the economic and environmental analyses. Chapter 5 covers the results of the economic and environmental analyses of four demonstration processes for the chemical recycling routes (solvolysis, depolymerisation, pyrolysis and gasification) of plastic packaging materials.

4.1 Identifying the promising input streams of plastic packaging materials

In its report “Exploration of chemical recycling,” CE Delft identified the promising streams of plastic packaging waste[27] that are currently not being recycled at all or only with limited possible applications for the recyclate. Depending on the chemical recycling route, these promising streams consist of:

1. Plastic packaging materials from the losses of sorting and recycling processes;
2. The stream of mixed plastics[28];
3. The mono-stream of PET trays, which is difficult to recycle at the moment.

Per ton of input for recycling, the environmental impact was calculated for the various recycling routes and compared to the current processing route. In the event of the loss of plastic material (for example during sorting), the current processing route is incineration with energy recovery. The stream of mixed plastics is used for example for products designed to replace other raw materials (including wood and virgin plastics). The mono-stream of PET trays is partially processed via miscellaneous sorted streams and stored, because nothing is currently being done with the majority of sorted PET trays. From 2018, 4PET will begin recycling a percentage of these PET trays[29].

When identifying the promising plastic waste streams, a distinction was made between the available streams from domestic plastic packaging waste that is already being collected (separately) and sorted and the plastic packaging materials that are disposed of by the office, retail and services sector. These streams are currently not collected separately at all – or only to a limited extent – and still contain a large percentage of plastic packaging materials that are potentially suitable for chemical recycling[30].

4.2 Method environmental impact

In order to identify the promising input streams of plastic packaging waste for chemical recycling, a demonstration process was defined for each main route of chemical recycling (see table 2). Each route

[27] The exploration of the possibilities of chemical recycling was inspired by the need for waste processing capacity and growing recycling ambitions in the plastic packaging market, not by the demand for fuels or chemicals. For that reason, plastic packaging materials (which make up 40% of the plastics that are put on the market every year) form the primary focus of this analysis.
[28] Whenever this analysis makes mention of the stream of mixed plastics, this refers to plastic packaging materials that are not recyclable via a mono-stream. These materials end up in the sorted streams according to the specifications DKR 350 or DKR 352. At some point in the future (to be determined), these specifications will be replaced by the new sorting specification for the Mixed Polyolefins (MPO) material stream.
[29] This will result in a recycling capacity of 18 kt per year for PET trays, once the capacity is fully operational and utilised. We assume that this line will process 18 kt of the annual volume of PET trays that is put on the market.
[30] The assessment listed in the proposed assessment framework outlined in chapter 1 also applies to the possibly separately collected streams of plastic packaging waste from the office, retail and services sector: which streams are suitable for mechanical recycling and which are suitable for chemical recycling?

varies in terms of its process steps and the required energy or excipients. This is partly dependent on the temperature that the technique requires. The environmental impact per ton of input was estimated by CE Delft based on the process steps of the chemical recycling route and the raw materials or fuels (and their associated production processes) that are avoided because of the use of the output product. The (positive or negative) environmental impact of the demonstration process in CO_2 equivalents per ton was then compared to the processing route that is currently being used for the plastic packaging stream in question. The impact of the various processing techniques is determined by:

- Direct emissions: the environmental impact of greenhouse gases emitted during the waste processing process itself (chemical recycling or the reference technique) and emissions that occur during the production and supply of excipients for the process.
- Avoided energy: the environmental impact of conventional energy production that is avoided with the waste processing process. One example is the production of electricity in a waste-to-energy plant, which means the use of fossil fuels is avoided.
- Avoided materials: the environmental impact of the conventional production of materials that is avoided with the waste processing process. One example is the production of BHET monomers through the magnetic depolymerisation of PET packaging waste. This means fewer fossil resources are needed for the production of PET.

The system limits for the calculations range from the moment at which the sorted plastic packaging waste streams arrive at the recycler to the moment at which the output streams (listed per technique in table 2) are ready. For the solvolysis and depolymerisation processes, the output consists of monomers and polymers from which all additives have been removed and which are suitable for reuse. For the demonstration process of pyrolysis, the calculations are based on an output that consists of naphtha, diesel and gas, which are partly used as raw materials and partly as fuel. The calculations for the demonstration process for gasification are based on an output that consists of syngas that is turned into methanol, which is then used for the production of new raw materials. Using the output products naphtha and methanol as raw materials requires additional processing steps, such as distillation or cracking. These processing steps fall outside the system limits for the calculation of the environmental impact and process costs, since the naphtha and chemicals from the recycling process replace fossil raw materials that would undergo a similar process as virgin raw materials in order to produce plastics.

		Assessed demonstration processes		
Group	**Technique**	**Demonstration process**	**Input**	**Output**
Chemical recycling	Solvolysis	Creasolv	EPS	PS, Bromine
	Depolymerisation	PET glycolysis	PET	rPET or BHET
	Pyrolysis	Rapid low-temperature pyrolysis	Mixed plastics	Naphtha, diesel, gas
	Gasification	High-temperature gasification	Recycle losses	Methanol
References (current processing)	Incineration		Recycle losses	Electricity, heat
	Mechanical recycling of PET		PET	rPET
	Mechanical recycling of mixed plastics		Mixed plastics	Plastic granulate, heat

Table 2: Overview of the demonstration processes that were assessed for the economic and environmental analyses, the (reference) techniques and the input and output streams used for the calculations in the analysis.

4.3 Method analysis process costs

To calculate the process costs of the four chemical recycling processes, four demonstration processes were first developed. Next, the equipment needed for the installation (including heat and mass balances) was estimated for these four processes. This results in the investment costs (CAPEX). Then the operational costs (OPEX) or production costs were calculated by including different factors (for example feedstock price, labour, maintenance, overhead) based on commonly used literature factors in the (petro)chemical industry[31]. Based on this information, the costs of the execution of this process (and any pre-processing steps) were calculated within a certain range.

The maximum attainable profit per ton is the difference between the maximum revenue (the sales price of the product per ton multiplied by the number of tons produced) minus the production costs of the product (per ton). This number indicates the sum that is left after the production and sale of the product. This is known as the EBITDA: the Earnings Before Interest, Taxes, Depreciation and Appreciation (or the gross profit). This number therefore does *not* include the costs and revenue of the financing (for example the depreciation of the facility or the interest on loans). For a complete picture or business case calculation, these factors will have to be accounted for over time (which means assumptions have to be made concerning the financial parameters). For the purposes of this study, the EBITDA was used because it indicates whether the process itself can result in a positive gross profit figure and because the process costs analysis is still plagued by uncertainties.

[31] The method used in this analysis includes twelve factors that affect the operational costs. This is a conservative estimate and a “theoretical” approach. However, it turned out that stakeholders only look at four factors in practice. This results in a different (more positive) estimate: this is the “practical” approach. In order to show the differences between these two approaches to estimating the figures, the figures for both the “theoretical” and the “practical” approach are included.

The following assumptions were used in the calculations of the OPEX and CAPEX of the four demonstration processes:

- The quality of the output products (polymer, monomer/building blocks, fuels or chemicals) is similar to that of the virgin material and they are sold for the same price;
- The scale of the facility is based on expected volumes and knowledge of comparable pilot programmes that are being planned or have already been launched in Europe;
- For the demonstration processes of EPS Creasolv, PET glycolysis and rapid low-temperature pyrolysis, any necessary pre-processing steps are included in order to make the feedstock suitable for the chemical process in question.
- The facilities are operational 8,000 hours per year;
- The facilities have an economic lifespan of twenty years.

The modelled processes provide insight into the parameters that have the biggest impact on the costs of the recycling process. The process costs, the costs of the feedstock and the revenue of the output and investment costs provide insight into the economic performance and optimal scale within a certain range. The analysis of the process costs provides information about:

- The process costs of one specific demonstration process for each of the four technique clusters;
- The costs of the process in terms of investment costs: the capital costs, material costs, etcetera;
- The costs of the process in terms of operational costs: the process costs, energy costs, costs of the feedstock, etcetera;
- The margin per ton of output, calculated based on the costs of the feedstock and the revenue (positive or negative) of the output. This revenue was calculated based on the volume and composition of the output;
- The yield of the technique based on input mass versus output mass;
- The impact of scale on capital and process costs.

Finally, sensitivity analyses were conducted in the calculations for:

- The price of the feedstock (-300% and +300%);
- The process efficiency (50% - 99% yield);
- The scale of the installations (10 kt/year - 300 kt/year);
- The oil price (the current oil price -50% and +50%).

4.4 Available streams of plastic packaging waste

One of the basic principles of this analysis is the fact that the streams of plastic packaging waste that are currently difficult or impossible to recycle mechanically are promising for chemical recycling. The plastic packaging streams that are recycled mechanically must possess a certain degree of purity in order to guarantee the quality of the recyclate. Plastic composites, laminates, paper stickers or labels and organic residue all impede the recycling process. Furthermore, the presence of (non-plastic) contaminants and certain types of films can cause the mechanical recycling equipment to jam. Lastly, odours are also a factor. At the moment, mechanically recycled plastic from packaging materials that have been collected via household waste collection systems or as industrial waste is unsuitable for food-grade applications[32]. Plastic packaging materials can go through a limited number of recycling processes, because the quality of the material declines after each cycle. In order to retain the desired quality, it is necessary to add virgin plastic to the recyclate

At the moment, there are various possible applications for mechanically recycled PE, PP and PET. As a result, there is a demand for these sorted and recycled plastic streams. However, the quality of the recyclate varies more than that of virgin plastics. Furthermore, the prices of the recyclate cannot compete with those of virgin plastics, for example due to the currently low oil price. This means that virgin plastics are often more appealing to buyers. Chemical recycling can potentially add value to a sorted mono-stream such as PET by increasing the purity of the material and removing any additives or colourants. This results in more potential applications and sales opportunities, for example food-grade applications.

4.4.1 Mixed plastics

At the moment, the use of chemical recycling is mostly economically viable for the stream of mixed plastics, sorted according to the DKR 350 or DKR 352 specification, where various types of plastics end up together. This stream makes up circa 35% of the total volume of sorted plastic packaging materials and is difficult to recycle mechanically. In 2015, the stream of mixed plastics from households consisted of 54.1 kt of material[33]. In this analysis, the stream of 54.1 kt of mixed plastics is seen as a promising input stream for a pyrolysis or gasification process. The output of the demonstration processes that were evaluated consists of a mix of naphtha, syngas and diesel (pyrolysis) or only syngas (gasification). These outputs can be used as raw material by for example the chemical industry or as building blocks for e.g. plastic. They can also be used as fuel, although the process is not classified as recycling in that case. The chemical recycling of the stream of mixed plastics offers added value compared to mechanical recycling because the current mechanical recycling of this material can be seen as relatively low-grade recycling. The output material is mainly used for thick-walled applications such as benches, tables and tiles.

For the assessment of the environmental impact and the process costs, the assumption was made that the composition of the stream of mixed plastics is similar to the sorting specifications based on which the collection and sorting fees are paid out.

4.4.2 Plastic packaging materials from sorting and recycling losses

During the sorting and recycling of source- and subsequently separated plastic packaging materials, some of these packaging materials are eliminated and end up as sorting and recycling losses. This is caused by for example the composition of the collected plastic after collection and the speed and accuracy of the sorting process. Mass balances from 2015 reveal that the sorting and recycling losses consist of (virtually) pure plastic[34]. These plastic packaging materials and non-packaging materials do

[32] One of the guidelines of the EFSA – it must be possible to trace back at least 95% of the material in the recycling process to material that comes from the food industry – impedes the large-scale application of recycled plastics for plastic packaging materials for food products. The origins of packaging materials that are collected via comprehensive collection systems or subsequent separation are untraceable, with the exception of PET bottles from the deposit refund stream.

[33] Exploration of chemical recycling, CE Delft, September 2018

[34] Environmental analysis of the recycling of plastic packaging materials, CE Delft, 2015

not end up in the stream of plastics that will be recycled mechanically, yet they may be suitable for chemical recycling. In total, circa 52 kt of material is lost from the recycling chains per year. The expected composition of the volume of plastic packaging materials that is lost during sorting and recycling is detailed in CE Delft's environmental analysis.

The losses from the recycling steps are currently incinerated in a waste-to-energy facility. Processing this stream via chemical recycling can produce plastics with a quality similar to that of virgin material. The plastic packaging materials in the recycling losses are suitable for pyrolysis or gasification. The output of these processes is a mix of naphtha, syngas and diesel or just syngas, respectively. These products can be used as raw materials for the chemical industry or as fuel.

4.4.3 Difficult to recycle mono-streams

A mono-stream that is currently not being recycled for the most part is the stream of PET trays. This is a collective name for PET packaging materials that are not bottles or flasks, such as trays, cups and clamshells. The use of PET trays has increased significantly in recent years. In recent years, the trays have been partially sorted as a mono-stream. They also make up a small percentage of other sorted plastic packaging waste streams[35]. To a limited extent, PET trays can be recycled along with PET bottles. There is an upper limit to the volume of PET trays in the PET mono-stream (DKR 328-1). Furthermore, the sorted PET tray stream can be recycled as part of the stream of mixed plastics. Once again, there is an upper limit of 10% in accordance with the sorting specification for mixed plastics (in accordance with the DKR 350 and DKR 352 sorting specifications).

In 2016, the KIDV introduced a sorting specification for PET trays. For the assessment of the environmental impact and the process costs, the assumption was made that the composition of the mono-stream of PET trays meets the sorting specifications for PET trays.

The total volume of PET trays that is put on the market in the Netherlands every year is estimated at 30 kt. Furthermore, a volume of sorted PET trays has been stored for eventual recycling. In the second half of 2018, the 4PET recycling line for PET trays will be launched. This will result in a recycling capacity of 18 kt of PET trays per year, once the capacity is fully operational and utilised. We assume that 4PET will process 18 kt of the volume of PET trays that is put on the market every year.

The sorted stream of PET trays is currently being stored until it can be recycled. With depolymerisation, the mono-stream of PET trays can be recycled into monomers with a quality similar to that of virgin material. The output can be reused for the production of plastics for (food-grade) packaging materials or applications.

[35] PET trays: the path towards structural solutions, KIDV 2016.

5 Results of the economic and environmental analyses per technique

This chapter describes the possible input and output streams for each main route of chemical recycling of plastic packaging materials. Next, the results of the economic and environmental analyses of four demonstration processes for chemical recycling routes of plastic packaging materials (solvolysis, depolymerisation, pyrolysis and gasification) are described per route. The economic analysis shows the process costs within a certain range using modelled demonstration processes, as well as the effects of factors such as the costs of the input stream, the scale of the process and the fluctuating oil price.

5.1 Solvolysis

Solvolysis is a physical process in which a solvent is used to dissolve polymers and separate them from other materials. For the economic and environmental analysis of solvolysis, a Creasolv process was modelled as a demonstration process. It uses EPS (with brominated flame retardants) from the construction sector as its input stream.

At the moment, there is no clear stream of packaging materials that can be processed using solvolysis. In the long run, the technique can offer added value for the recycling of plastic packaging materials, for example when it is economically viable to separate the layers in multi-layer PE and PP packaging materials from other materials because there is a sufficient demand for the higher-grade recycling of multi-layer packaging materials. These packaging materials are currently recycled using mechanical techniques (although this limits the possible applications of the recyclate because these packaging materials end up in the stream of mixed plastics or are lost during sorting or recycling and then incinerated). Solvolysis therefore has a special position in this analysis: it is not (yet) an obvious technique to use for the recycling of plastic packaging materials, yet the scale at which the solvolysis of EPS from the construction sector (i.e. non-packaging materials) can be conducted does contribute to the ambition of 250 kt output from chemical recycling as defined in the Transition Agenda for Plastics.

Solvolysis is used to separate plastics from additives or other materials, for example for products from other sectors such as the electronics or automotive sectors or for composite materials. At the pilot scale, solvolysis is used to recycle expanded polystyrene (EPS), which is commonly used as an isolation material in the construction sector and has been processed with flame retardants. The EPS is separated from the brominated flame retardants, after which the polymers are extracted from the solvent and processed into clean polystyrene (PS). The requirements for the feedstock of solvolysis in terms of its homogeneity and purity are fairly high. This means that a clean plastic stream with less than 10% contamination is needed.

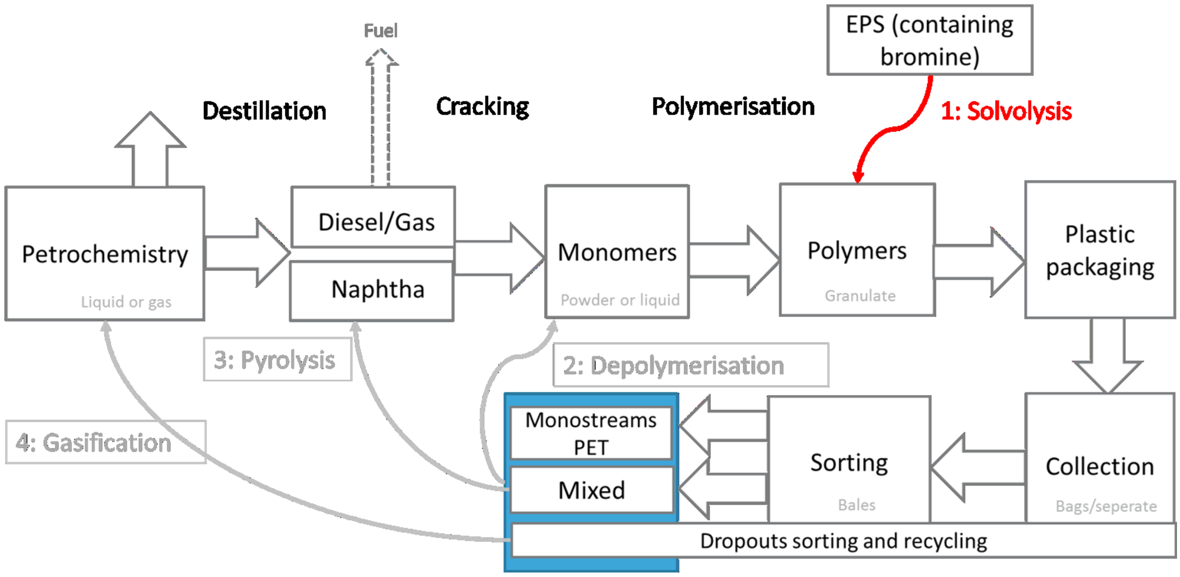

Image 2: A schematic overview of the demonstration process for solvolysis (with brominated EPS as input and polystyrene as output) in the plastic packaging chain.

5.1.1 Input and output streams

The EPS suitable for the demonstration process for solvolysis is found in limited quantities in plastic packaging waste. At the moment, plastic packaging waste from households consists of 3% EPS, which is collected at waste collection facilities or as part of the residual waste stream. In total, 13 kt of EPS packaging material is put on the market every year and disposed of by households and businesses[36]. This stream can easily be recycled mechanically. The chemical recycling of the EPS from packaging materials is therefore not an obvious choice at the moment.

EPS is used in larger quantities in the construction sector, where it has a longer cycle of use than when used for packaging materials. Every year, 6.5 kt of EPS is disposed of by the construction sector[37]. This material must be separated from the brominated flame retardants it has been processed with. Solvolysis is a promising technique for this purpose. At the moment, the material is incinerated with energy recovery.

For this analysis, we only use the volume of EPS from the construction sector, because EPS from packaging materials can be recycled using mechanical techniques at the moment. However, EPS is only collected and sorted for recycling on a very limited scale in the Netherlands. Which products are left after dissolution of the materials depends on the input streams. For the EPS from the construction sector, those are polystyrene (PS) and bromine, as well as the solvent itself (which can be reused for multiple solvolysis processes).

[36] Based on various data from Research of plastic waste streams in the Netherlands, RVO, 2011 / Presentation Post-consumer plastic waste management in European countries, NRK, 2013 / Plastics with hazardous substances: recycle or incinerate? RIVM, 2015.
[37] Plastics with hazardous substances: recycle or incinerate? RIVM, 2015.

5.1.2 Environmental impact

In this analysis, only the stream of EPS with brominated flame retardants from the construction sector is viewed as an available stream for solvolysis. For the calculation of the environmental impact, incineration with energy recovery was used as a reference technique[38]. Compared to incineration, solvolysis offers a positive environmental impact of 3.2 tons of CO_2 equivalents per ton. This is comparable to the positive environmental impact of the mechanical recycling of EPS compared to incineration. The environmental benefits mainly come from the avoided production of PS. However, the calculation is uncertain and therefore represents a conservative estimate, because assumptions have been made about the loss of solvent and the energy requirements of the process.

The advantage of solvolysis is that the quality of the recyclate is high, because additives and colourants are removed from the material. Furthermore, solvolysis is a fairly low-energy process with a high yield of raw materials and limited loss of the solvent.

Environmental impact	
Compared to incineration in a waste-to-energy facility	-3.2 tons of CO_2 eq./ton input

5.1.3 Process costs of the demonstration process for solvolysis (EPS Creasolv)

For the calculation of the process costs and EBITDA[39] of a demonstration process for solvolysis (of brominated EPS), the Creasolv process was used. A feedstock price of €50 per ton of EPS and a sales price of €1,720 per ton of PS were used for the calculation.
For a capacity of 20 kt of input per year, the investment costs are €26.1 million and the annual operational costs are €12.1 million[40]. The following aspects of the model calculation of the process costs stand out:

- The production costs are €672 per ton of feedstock (baseline calculation, see diagram 1);
- The operational costs make up the majority of the production costs. The energy costs make up most of the OPEX (because of the distillation and drying involved in the process), followed by the labour costs and feedstock costs;
- The production costs are high, yet an EBITDA of €962 per ton of feedstock is possible (baseline calculation). This is due to the high value of the output product PS, which can immediately be used by the plastics industry;

[38] The stream of EPS in packaging materials (13 kt on the market every year) is currently recycled mechanically and makes for a less obvious choice for recycling via solvolysis. The analysis of the environmental impact therefore does not involve a comparison with mechanical recycling, but with incineration with energy recovery.
[39] The maximum attainable profit per ton is the difference between the maximum revenue (the sales price of the product per ton multiplied by the number of tons produced) minus the production costs of the product (per ton). This number indicates the sum that is left after the production and sale of the product. This is known as the EBITDA: the Earnings Before Interest, Taxes, Depreciation and Appreciation (or the gross profit). This number therefore does *not* include the costs and revenue of the financing (for example the depreciation of the facility or the interest on loans).
[40] An analysis of the production costs and gross profits of four chemical recycling processes, TNO by order of the KIDV, October 2018.

- The process scale and the oil price largely determine the value of the EBITDA. The oil price affects the EBITDA because of the high value of the output product, which approaches that of the plastic granulate. It can be sold at a higher price when the oil price increases.

	EPS Creasolv (scale 20 kt/year)
CAPEX (M€)	26.1
Process costs (OPEX M€/year)	12.1
Feedstock price (€/ton feedstock)	50
Process efficiency (mass %)	95%
Output price (€/ton product)	1,720 (PS)
Production costs (€/ton feedstock)	672
EBITDA (€/ton feedstock)	962

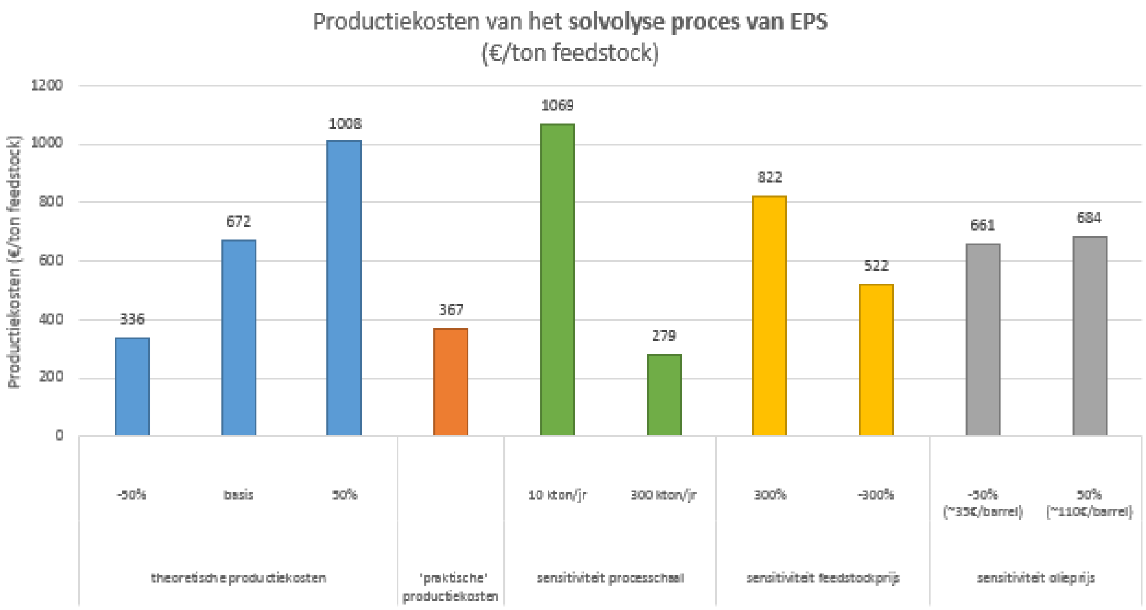

Diagram 1: The production costs of the EPS Creasolv demonstration process.

5.2 Depolymerisation

Similar to solvolysis, depolymerisation involves the dissolution of plastic packaging materials using solvents and heat. The material is heated at a relatively low temperature, which breaks down the chemical bonds of the plastic chains and produces shorter chains and monomers. These monomers can then be polymerised to create plastic. Depolymerisation can only be used for a specific group of plastics, the so-called polycondensates. For the economic and environmental analysis of depolymerisation, PET glycolysis was modelled as a demonstration process.

An advantage of depolymerisation is the fact that impurities are removed from the plastic and left behind in the solvent. This includes colourants and insoluble plastics used in multi-layer packaging materials. The output of depolymerisation is potentially suitable for food-grade applications. The requirements for the input stream in terms of its homogeneity and purity are fairly high. For this analysis, we assume that depolymerisation is a suitable technique for the recycling of the available stream of PET trays. The output of this process consists of rPET and BHET.

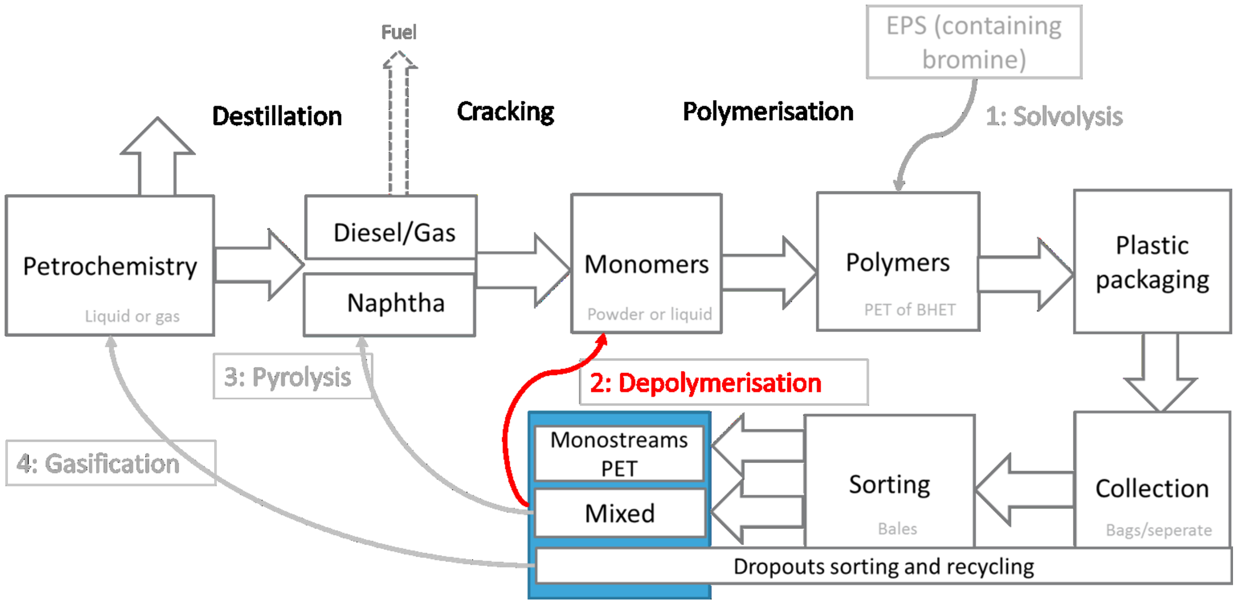

Image 3: A schematic overview of the demonstration process for depolymerisation (with PET trays as input and rPET and BHET as output) in the plastic packaging chain.

5.2.1 Input and output streams

PET bottles and trays (including contaminants) can be used as input streams for depolymerisation. Other products, such as textile or products that include PET, can also be processed using depolymerisation. For this analysis, the stream of PET trays that is put on the market every year was used, because this stream is currently not being recycling using mechanical techniques. Part of this stream is collected via the household waste stream, part of it via industrial waste (including the waste from the office, retail and services sector) and part of it is lost in the residual waste stream or during sorting and recycling. In 2018, 4PET will begin processing part of the stream of PET trays put on the market every year.

Additionally, it is possible to process the sorted stream of PET (DKR 328-1) via depolymerisation. Every year, 11 kt of PET from households is sorted in accordance with the DKR 328-1 specification[41]. Processing this stream via depolymerisation is a less obvious choice at the moment, because there currently exists an excellent sales market for the mechanical recycling of the DKR 328-1 stream. However, the growing demand for rPET that is suitable for food-grade applications or from which colourants and other additives have been removed increases the chance that (part of) the DKR 328-1 PET stream will ultimately be processed via depolymerisation.

[41] The method used to calculate the available quantities of plastic packaging waste in 2020 and 2030 and the underlying assumptions are outlined in An exploration of chemical recycling, CE Delft, September 2018.

5.2.2 Environmental impact

Because PET trays are not currently recycled as a mono-stream, no data is available about the associated positive environmental impact compared to incineration. For the environmental analysis, the depolymerisation of PET trays is therefore compared to the storage of these trays, the mechanical recycling of PET bottles and incineration in a waste-to-energy facility. The comparison with mechanical recycling is not entirely sound, however, because mechanical recycling currently cannot process large quantities of contaminants and additives as well as depolymerisation

The depolymerisation of PET trays results in a positive environmental impact of -1.5 tons of CO_2 equivalents per ton compared to doing nothing, i.e. storing the trays, which is what currently happens to a large percentage of the PET trays. Compared to the mechanical recycling of PET, the depolymerisation of PET trays results in a negative environmental impact of 0.8 tons of CO_2 equivalents per ton (compared to the incineration of PET).

However, the advantage of depolymerisation compared to mechanical recycling lies in the fact that the rPET can be used for food-grade applications and that colourants and other additives are removed from the material. When PET trays are recycled mechanically, additional processing steps are required to make the rPET suitable for food-grade applications. It is estimated that, in terms of its environmental impact, the depolymerisation of PET trays is ultimately comparable to the mechanical recycling of PET which is then made suitable for food-grade applications. Another advantage of depolymerisation compared to mechanical recycling is that the material can go through more recycling processes, because the quality of the material increases rather than decreases after recycling.

For both mechanical and chemical recycling, the avoided production of virgin PET offers a positive environmental impact compared to incineration. Once the 4PET recycling line is fully operational, the processing of PET trays can be used as a reference.

Environmental impact	
Compared to incineration in a waste-to-energy facility	-3.1 tons of CO_2 eq./ton input
Doing nothing, i.e. storing the trays	-1.5 tons of CO_2 eq./ton input
Compared to the mechanical recycling of PET with no additional processing steps	+0.8 tons of CO_2 eq./ton input

5.2.3 Process costs of the demonstration process for depolymerisation (PET glycolysis)

For the calculation of the process costs and EBITDA of a demonstration process for the depolymerisation of plastic packaging materials, the glycolysis process[42] of PET was used. A feedstock price of €100 per ton of PET and a sales price of €960 per ton of rPET were used for the calculation.

[42] Glycolysis is a depolymerisation process in which glycolysis is added to depolymerise PET to produce BHET (bis(2-hydroxyethyl) terephthalate).

For a capacity of 20 kt of input per year, the investment costs are €18.7 million and the annual operational costs are €11.2 million[43]. The following aspects of the model calculation of the process costs stand out:

- The production costs are €605 per ton of feedstock (baseline calculation, see diagram 2);
- The operational costs make up the majority of the production costs. The energy costs make up most of the OPEX (because of the distillation and drying involved in the process), followed by the labour costs and feedstock costs;
- An EBITDA of €307 per ton of feedstock is possible (baseline calculation) because of the high value of the output product, which can immediately be used by the plastics industry;
- The process scale, the oil price and the feedstock price all have a major impact on the EBITDA: with a small process scale, a high feedstock price and a high oil price, the profit can turn into a loss. With a favourable combination of these parameters, a positive EBITDA may be expected.

	PET glycolysis (scale 20 kt/year)
CAPEX (M€)	18.7
Process costs (OPEX M€/year)	11.2
Feedstock price (€/ton feedstock)	100
Process efficiency (mass %)	95%
Output price (€/ton product)	960 (rPET)
Production costs (€/ton feedstock)	605
EBITDA (€/ton feedstock)	307

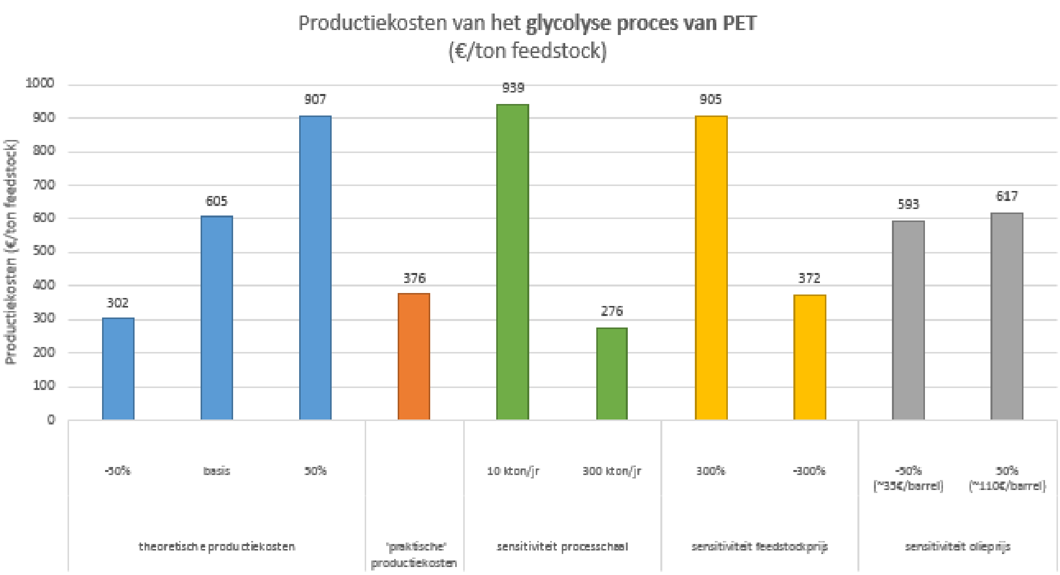

Diagram 2: The production costs of the PET glycolysis demonstration process

[43] An analysis of the production costs and gross profits of four chemical recycling processes, TNO by order of the KIDV, October 2018.

5.3 Pyrolysis

For the economic and environmental analysis of the pyrolysis technique, a process of rapid low-temperature pyrolysis of plastic packaging materials is used as a demonstration process. In practice, the economic and environmental impact will differ per pyrolysis process. The findings are indicative of the process costs and the potential environmental impact of pyrolysis as a technique (a collective term for multiple processes) used for the recycling of mixed plastics. The results of the pyrolysis of for example wood, biomass and car tyres may differ significantly. During the process of rapid low-temperature pyrolysis, heating the feedstock at 400 to 600 degrees Celsius produces a fuel. Through heating, the polymer chains in the plastic are broken down, which produces products with a shorter chain length. The lack of oxygen ensures that no incineration occurs.

Pyrolysis is suitable for polyolefins used in packaging materials, for example PE, PP and PS. The requirements for the feedstock of pyrolysis in terms of its homogeneity and purity are limited, compared to the feedstock requirements of solvolysis and depolymerisation processes.

The output of the demonstration process consists of naphtha, gas and diesel. These materials can be used as fuel or as raw materials for the chemical industry. For example, naphtha is a valuable chemical product that can immediately be used for the production of new plastics. In this analysis, a process is defined as chemical recycling when its output is reused as raw material (see chapter 3.1).

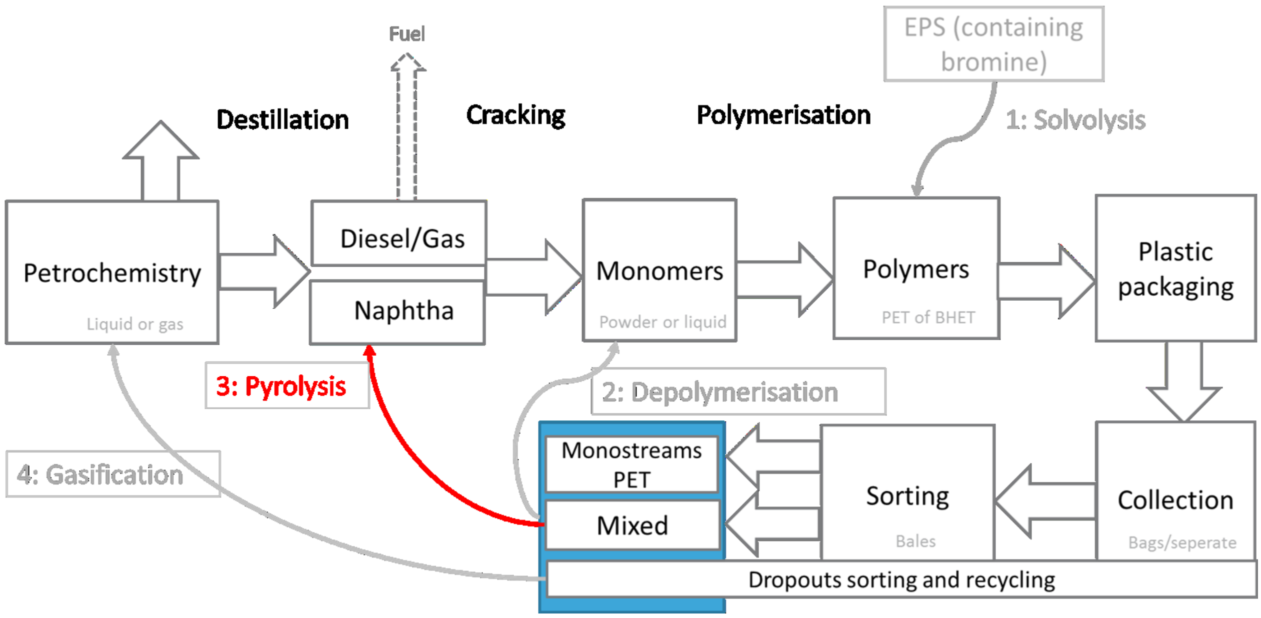

Image 4: A schematic overview of the demonstration process for pyrolysis (with the stream of mixed plastics as input and a mix of naphtha, diesel and gas as output) in the plastic packaging chain.

5.3.1 Input and output streams

For this analysis, the available stream of mixed plastics is seen as suitable and available input for pyrolysis. The plastics in recycling losses can also be processed with pyrolysis. However, the current composition of the sorting and recycling losses contains too much PET and PVC, which means an additional pre-processing step is required. In total, an annual volume of 114 kt of mixed plastics and plastic packaging materials from recycling losses is available from households. These plastic packaging materials can be processed with a pyrolysis process[44]. Whether the process is classified as chemical recycling according to the definition used in the National Waste Management Plan 3 (see chapter 3.1) depends on the ratio of the resulting naphtha, gas and diesel and how these output products are then used: as raw materials or as fuel.

5.3.2 Environmental impact

For the analysis of the environmental impact, processing the sorting and recycling losses with pyrolysis has been compared to incineration with energy recovery, because this is the processing route that is currently being used. Pyrolysis offers a positive environmental impact of -1.7 to -1.9 tons of CO_2 equivalents per ton, compared to incineration. This is due to the fact that the direct emission of greenhouse gases during the process is lower. The production of fuel means other production chains (natural gas, diesel) are avoided, although this process is not classified as recycling according to the definition used in this report. Compared to the mechanical recycling of the stream of mixed plastics, pyrolysis has a comparable environmental impact or a negative environmental impact of 0.2 tons of CO_2 equivalents per ton of input. A point of attention is the fact that the mechanical recycling of the stream of mixed plastics offers a lower CO_2 reduction per ton: circa half of the positive environmental impact of the recycling of plastic mono-streams. On the other hand, the mechanical recycling of mixed plastics does contribute to the reduction of the use of tropical hardwood. In other words, the standard for a performance equal to that of the mechanical recycling of mixed plastics is lower than the standard for plastic mono-streams.

Environmental impact	Pyrolysis of recycling losses	Pyrolysis of mixed plastics
Compared to the mechanical recycling into plastic recyclate for thick-walled applications.		0 to +0.2 tons of CO_2 eq./ton input
Compared to incineration in a waste-to-energy facility	-1.7 to -1.9 tons of CO_2 eq./ton input	

5.3.3 Process costs of the demonstration process for pyrolysis (rapid low-temperature pyrolysis)

For the calculation of the process costs and EBITDA of a demonstration process for the pyrolysis of plastic packaging materials, the process of rapid low-temperature pyrolysis was used. A negative feedstock price of - €50 per ton of mixed plastics was used for the calculation (meaning that the recycler is paid to accept the stream of mixed plastics), as well as an average sales price that consists of € 400 per ton of diesel, € 500 per ton of naphtha and € 800 per ton of gas.
For a capacity of 30 kt of input per year, the investment costs are €25.4 million and the annual operational costs are €8.0 million. It was assumed that 21,000 kt of diesel, 5,000 kt of naphtha and

[44] If the waste from the office, retail and services sector was to be separated, sorted and recycled in a similar manner, this could result in an annual input volume of 84 kt for pyrolysis.

2,000 kt of gas are produced every year[45]. The following aspects of the model calculation of the process costs stand out:

- This calculation of the process costs is based on the assumption that the feedstock stream consists almost entirely of plastics (DKR 350 or DKR 352). In practice, other plastic waste streams are also used, since pyrolysis can handle those streams as well. Which streams are used and mixed together depends on for example the composition, degree of contamination and price of the input streams and the desired output products. The other streams that are processed are relevant for the business case and upscaling potential of pyrolysis. The benefit of using streams that mainly consist of clean plastics is that fewer investments in the pre-processing and cleaning of the products are needed, which results in a lower CAPEX and OPEX;
- The production costs are €310 per ton of feedstock (baseline calculation, see diagram 3);
- The operational costs make up the majority of the production costs. The labour and overhead costs make up most of the OPEX. The energy requirements are less of a factor for this process, since energy is generated by incinerating the off-gas that is produced[46]. This energy can then be used to power the pyrolysis process. As a result, the process is less sensitive to long-term fluctuations of the energy price;
- The investment costs are mainly affected by the costs of the reactor and the scrubber;
- An EBITDA of €100 per ton of feedstock is possible (baseline calculation);
- The process scale, the oil price and the feedstock price all have a major impact on the EBITDA: with a small process scale, a high feedstock price and a high oil price, the profit can turn into a loss. With a favourable combination of these parameters, a positive EBITDA may be expected;
- The scale of the process is a major factor. The production costs of a large-scale process are dominated by the OPEX rather than the CAPEX, which results in positive scale effects. Pyrolysis installations perform better at a larger scale: the production costs are significantly reduced, while the potential EBITDA significantly increases;
- Another feedstock stream that was evaluated is the stream of sorting residue. Due to the different composition and energetic value of this stream, the production costs are slightly higher (€340 per ton of feedstock), as is the EBITDA (€108 per ton of feedstock).

	Rapid low-temperature pyrolysis of mixed plastics (scale 30 kt/year)
CAPEX (M€)	25.4
Process costs (OPEX M€/year)	8.0
Feedstock price (€/ton feedstock)	-50
Process efficiency (mass %)	90%
Average output price (€/ton product)	600 (naphtha) 500 (diesel) 800 (gas)
Production costs (€/ton feedstock)	310
EBITDA (€/ton feedstock)	100

[45] An analysis of the production costs and gross profits of four chemical recycling processes, TNO by order of the KIDV, October 2018.

[46] One of the output products of the demonstration process for pyrolysis is off-gas (10%). Part of this off-gas is used for heating during the process, while the rest is used for the production of LPG.

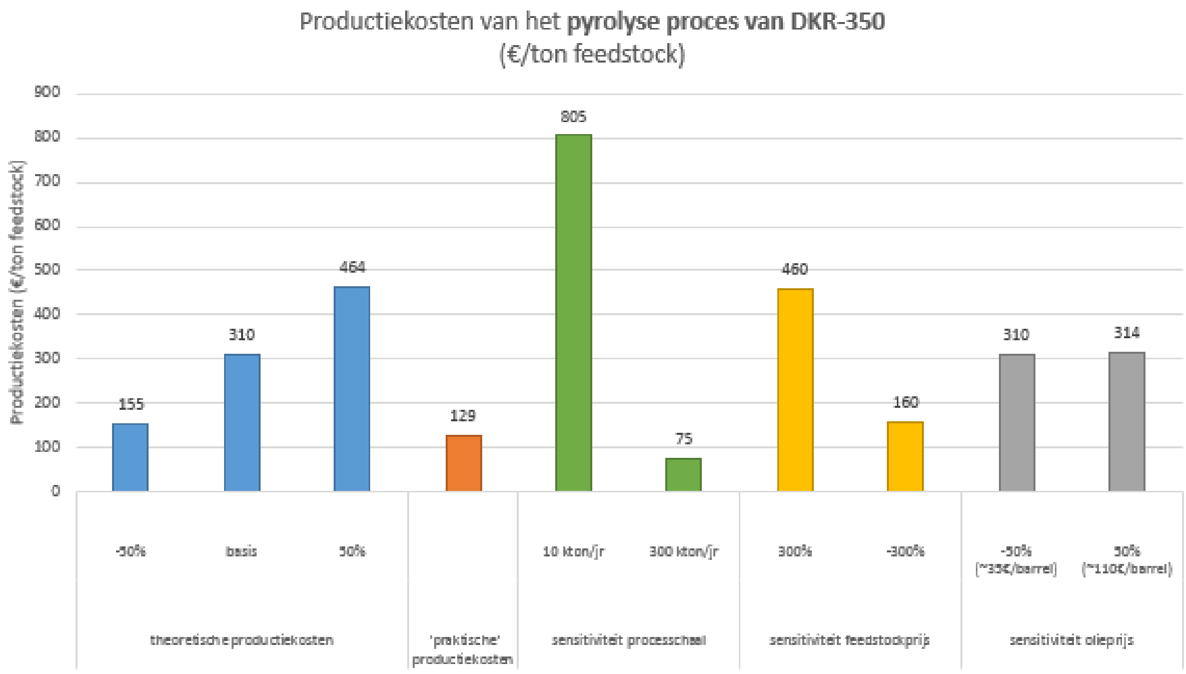

Diagram 3: The production costs of the rapid low-temperature pyrolysis demonstration process.

5.4 Gasification

Like pyrolysis, gasification is a collective term for a number of different processes. For the economic and environmental analysis, a process of high-temperature gasification of plastic packaging materials was used. In practice, the economic and environmental impact will differ per gasification process. The findings are indicative of the process costs and the potential environmental impact of gasification as a technique (a collective term for multiple processes) used for the recycling of mixed plastics. The results for the gasification of for example residual streams and biomass may differ significantly. During the process of high-temperature gasification, the feedstock is heated at 800 to 1,000 degrees Celsius and oxygen is added. Through high-temperature gasification, the feedstock is broken down into molecules (a combination of H_2 and CO molecules), which produces syngas. Depending on its quality, this syngas may be suitable for processing into methanol by the chemical industry and form the foundation for new monomers. However, this route requires a number of additional processing steps. The output of gasification may also be added to fuels. In that case, the process is not classified as chemical recycling according to the definition used in the National Waste Management Plan 3.

The requirements for the feedstock of gasification in terms of its homogeneity and purity are limited, compared to the feedstock requirements of solvolysis and depolymerisation processes. Gasification is less sensitive to fluctuations in the feedstock. However, a pre-processing step is required to make the (currently) available plastic packaging streams suitable for gasification. Non-deformable plastic packaging materials can be processed, but the process can also accommodate a limited quantity of PVC, films and multi-layer materials. Plastic packaging materials make up only part of the total feedstock for gasification. Circa 20% of the feedstock consists of plastic; this ratio determines the total feedstock price and the business case.

In this analysis, a process is defined as chemical recycling when its output is reused as raw material (see chapter 3.1). When the gasification of plastic packaging waste results in an output product that is used as fuel, the process is not classified as chemical recycling according to this definition.

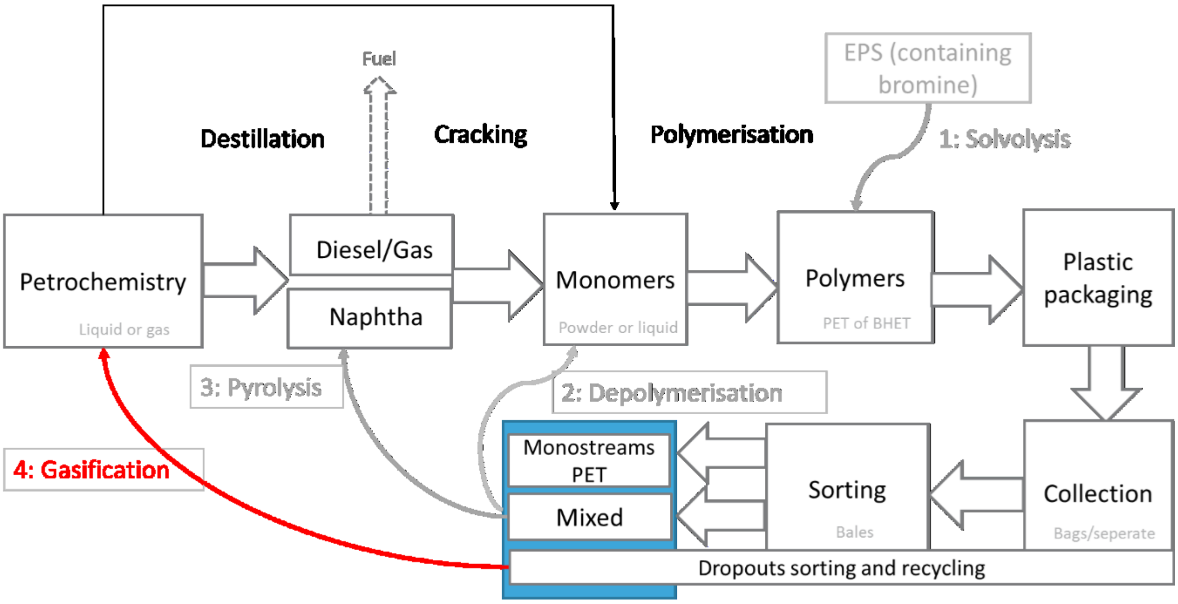

Image 5: A schematic overview of the demonstration process for gasification (with recycling losses in the plastic packaging chain as input and methanol as output).

5.4.1 Input and output streams

Plastic packaging materials make up only part of the total feedstock for gasification. The supply of plastic packaging materials as an input stream therefore has a limited impact on the viability of an installation. The plastic that is used for gasification is a "blend-in" (20-30% of the total feedstock) of other input streams, mainly biomass[47]. There are incentive measures for the conversion of biomass into biofuels that apply when (part of) the output is used as biofuel. The application of the syngas or methanol as (raw material for) fuel goes against the condition outlined in the National Waste Management Plan 3 to use the output of the recycling process "as a raw material for the manufacturing industry."

In total, an annual volume of 114 kt of mixed plastics and plastic packaging materials from recycling losses is available from households. These plastic packaging materials can be processed using a gasification process[48]. The output of gasification is syngas, which can be added to fuel or used for the production of methanol for the chemical industry. At the moment, methanol is mostly produced from natural gas or coal. The process of converting the syngas into methanol requires a lot of oxygen as an excipient.

[47] An analysis of the production costs and gross profits of four chemical recycling processes, TNO by order of the KIDV, October 2018.
[48] If the waste from the office, retail and services sector was to be separated, sorted and recycled in a similar manner, this could result in an annual input volume of 84 kt for gasification.

5.4.2 Environmental impact

The gasification of the sorting and recycling losses is compared to incineration with energy recovery, because this is the processing route that is currently used for these plastic packaging materials. Gasification results in a positive environmental impact of -2.3 tons of CO_2 equivalents per ton, compared to incineration. Compared to the current mechanical recycling of the stream of mixed plastics, gasification of the stream of mixed plastics offers a small positive environmental impact (-0.3 tons of CO_2 equivalents per ton of input).

Environmental impact	Gasification of recycling losses	Gasification of mixed plastics
Compared to the mechanical recycling into plastic recyclate for thick-walled applications		-0.3 tons of CO_2 eq./ton input
Compared to incineration in a waste-to-energy facility	-2.3 tons of CO_2 eq./ton input	

5.4.3 Process costs of the demonstration process for gasification (high-temperature gasification)

For the calculation of the process costs and EBITDA of a demonstration process for the gasification of sorting residue, the process of high-temperature gasification was used. The calculation uses a negative feedstock price of -€50 per ton of sorting and recycling losses (meaning that the recycler is paid to accept this stream), as well as an average sales price of €250 per ton of methanol.
For a capacity of 100 kt of input per year, the investment costs are €81.9 million and the annual operational costs are €40.8 million[49]. The following aspects of the model calculation of the process costs stand out:

- This calculation of the process costs is based on the assumption that a feedstock stream is used that largely consists of plastics (sorting and recycling residue). In practice, other waste streams are also used, since gasification can be used to process non-plastics as well. Which streams are used and mixed together depends on for example the composition and price of the input streams and the desired output products. The other streams that are processed are relevant for the business case and upscaling potential of gasification;
- The production costs are €449 per ton of feedstock (baseline calculation, see diagram 4);
- The operational costs make up the majority of the production costs. The costs of the industrial gases required for the process (hydrogen and oxygen) make up most of the OPEX. The energy requirements are less of a factor for this process, since energy is generated by incinerating the gas produced during the process. This energy can be used to power the gasification process. As a result, gasification is less sensitive to long-term fluctuations of the energy price;
- The investment costs are mainly affected by the costs of the gasification facility and the compressor;
- Converting the syngas that is produced during the gasification process into methanol requires industrial gases, for which supply capacity must be created. For the purposes of this

[49] An analysis of the production costs and gross profits of four chemical recycling processes, TNO by order of the KIDV, October 2018.

calculation, the assumption was made that this capacity is available in the environment or can be created with the help of chemical industry located nearby. However, these costs must be calculated when setting up an independent gasification facility;
- The EBITDA is negative: -€89 per ton of feedstock (in the baseline calculation);
- The process scale, the oil price and the feedstock price all have a major impact on the EBITDA: with a small process scale, a high feedstock price and a high oil price, the EBITDA will be negative. With a favourable combination of these parameters, a slightly positive EBITDA may be expected;
- The scale of the process is a major factor. The production costs of a large-scale process are dominated by the OPEX rather than the CAPEX, which results in positive scale effects. Gasification installations perform notably better at a larger scale. Setting up a small-scale gasification facility will therefore seriously impede the realisation of a positive EBITDA;
- Another feedstock stream that was evaluated is the stream of mixed plastics. Due to the different composition and energetic value of this stream, the production costs are slightly lower (€412 per ton of feedstock), while the EBITDA is slightly higher (-€82 per ton of feedstock).

	High-temperature gasification of sorting residue (scale 100 kt/year)
CAPEX (M€)	81.9
Process costs (OPEX M€/year)	40.8
Feedstock price (€/ton feedstock)	-50
Process efficiency (mass %)	143%[50] (>100% due to the addition of oxygen and hydrogen)
Average output price (€/ton product)	250 (methanol)
Production costs (€/ton feedstock)	449
EBITDA (€/ton feedstock)	-89

[50] Half of the mass of methanol comes from the addition of oxygen during the process of converting syngas into methanol: 1 kt of feedstock is converted into 1.43 kt of output product.

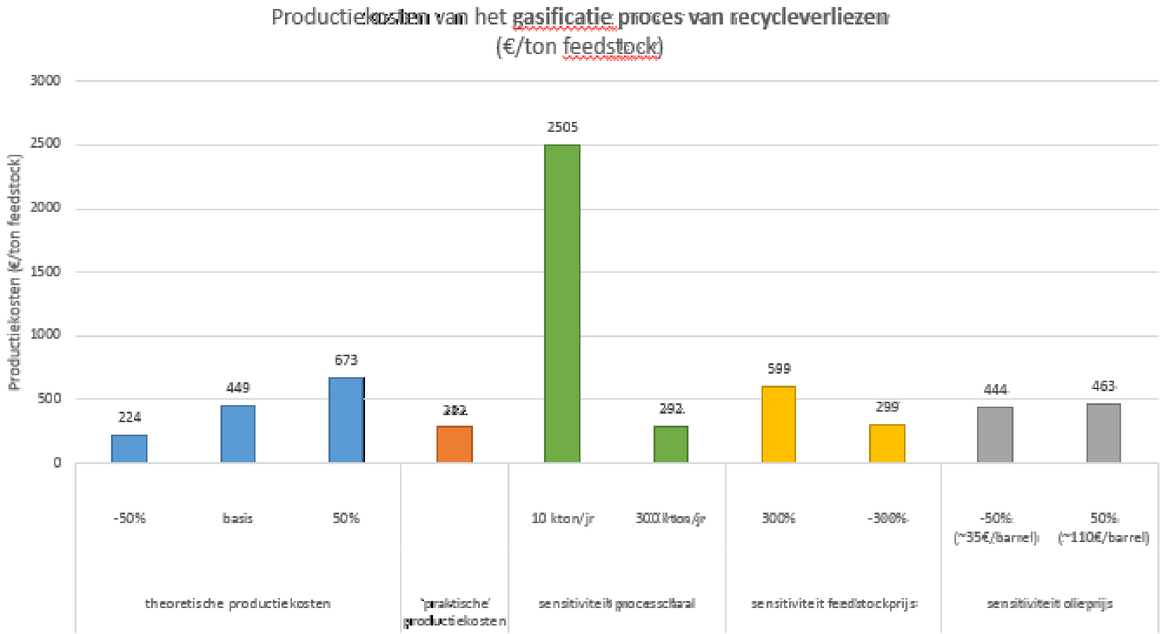

Diagram 4: The production costs of the high-temperature gasification demonstration process.

6 Opportunities and restrictions in terms of policies and regulations

Chemical recycling is becoming an increasingly prominent route for raw materials in order to close chains. This calls for regulations and policies that are tailored to this situation. For example, chemical recycling is seen as a new category of recycling (for example in the National Waste Management Plan) and there are incentive measures (for example the subsidies for chemical recycling from the Ministry of Economic Affairs and Climate Policy). Existing regulations already create certain opportunities and options for (the continued development of) new chemical recycling techniques. In some regards, the further concretisation of or leeway within regulations is needed in order to realise chemical recycling in the Netherlands. Agreements and regulations pertaining to packaging materials and waste management policies use various definitions for (chemical) recycling, see chapter 3.1.

The following description of opportunities and restrictions distinguishes between the conditions for the development of the chemical recycling of packaging materials at an industrial scale and application opportunities for the recyclate from chemical recycling. Finally, we will examine policy developments that may affect the available input streams for chemical recycling.

6.1 Chemical recycling in the National Waste Management Plan 3

The National Waste Management Plan 3 (LAP3) entered into force in late December of 2017 and will run from 2017 to 2023. In the waste hierarchy (see image 6), a distinction is made between a number of forms of recycling, based on the possible applications of the recyclate. Chemical recycling has been defined as the lowest form of recycling (c3). In order to stimulate the transition towards a circular economy, the government can incentivise the use of these forms of recycling, for example via minimum standards (licensing for certain forms of recycling) and via policies pertaining to the international transport of waste materials (limit this transport for low-grade applications). The LAP3 serves as the framework for these measures. Competent licensing authorities do not make their own considerations.

Image 6: The waste hierarchy from the National Waste Management Plan (LAP3).[51]

[51] Source: https://lap3.nl/beleidskader/deel-algemeen/b9-recycling-binnen/

In general, chemical recycling is seen as the lowest-grade form of recycling due to the often-high costs, the high energy requirements and the fact that the output cannot always immediately be used as a raw material. However, LAP3 states that its contribution to the transition towards a circular economy is significant enough in certain specific cases that chemical recycling is classified as the preferred recycling method anyway[52].

Volumes that are recycled into their original materials count as recycling and contribute to the realisation of the VANG targets[53]. Namely: 100 kg of domestic residual waste per person in 2020, combined with an increase of the recycling rate to 75% and 30 kg of domestic residual waste per person by 2025. Furthermore, the volume of industrial waste is expected to decrease by half: to 1.25 million tons in 2022. This means the Netherlands' ambitions are higher than those of Europe.

By explicitly including chemical recycling as a recycling category in the LAP3, a clear distinction is made between these chemical processes and energy recovery processes. The chemical process is only classified as a form of recycling when its output is used as raw material for the manufacturing industry, not as a fuel.

6.2 Chemical recycling and the government-wide Circular Economy programme

The government-wide Circular Economy programme, entitled "A Circular Economy in the Netherlands by 2050," was introduced in 2016. The programme is based on a halving of the use of primary raw materials by 2030 and the realisation of a fully circular economy by 2050. Realising this ambition will require major changes. Many parties play a role in the transition, including businesses, governments, knowledge institutes and social organisations. Parties have endorsed these ambitions in the Raw Materials Agreement. The ambitions are substantiated in the form of five transition agendas, including one for plastics. The Transition Agenda for Plastics includes the ambition to realise 10% chemical recycling of plastic packaging and non-packaging materials by 2030. The Action Plan Chemical Recycling[54] substantiates the ambition to realise the chemical recycling of 10% of all plastic waste with, among other things, an R&D programme, a clear definition and a distinction between various types of chemical recycling processes that fit within a national investment strategy for chemical recycling facilities. The Action Plan is being developed based on this analysis of the chemical recycling of plastic packaging materials.

6.3 Subsidies available for chemical recycling

To support the development of chemical recycling, the Ministry of Economic Affairs and Climate Policy offers a number of subsidies based on the Regulation National EA subsidies:

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[52] See the National Waste Management Plan 3, paragraph A.4.2.2.
[53] Van Afval Naar Grondstof (From Waste to Raw Material) programme, set up by the national government (Ministry of Infrastructure and Water Management), NVRD and the Association of Dutch Municipalities (VNG).
[54] Transition Agenda for Plastics, page 33, via:
https://www.rijksoverheid.nl/documenten/rapporten/2018/01/15/bijlage-3-transitieagenda-kunststoffen

- CO_2 reduction industry (Title 3.20, Regulation National EA subsidies): Subsidy is available for investments in the chemical recycling of plastics that results in CO_2 reduction. At least €1.5 million of the total subsidy limit of €17.5 million is set aside for chemical recycling.
- Biobased Economy, Green Gas and Recycling: Innovation projects (Title 4.2 Top Sector Energy Projects): Subsidy is available for pilot projects in the field of the chemical recycling of plastics. The total budget (which may be used for more than chemical recycling alone) is €3.1 million.

6.4 Concretisation and modification of regulations in order to incentivise the chemical recycling of plastic packaging materials

Condition: Classify chemical recyclers as certified recyclers

As part of the manufacturer responsibility system, producers and importers of packaging materials pay a contribution for the processing of the packaging materials they put on the market. The Packaging Waste Fund then pays municipalities for the collection and sorting of domestic packaging waste. The payment and measuring moment occurs at the recycler's front gate (the number of tons of plastic packaging material made available for recycling). This system is outlined in the Framework Agreement for Packaging (2013-2022).

It is not clear what will happen after the end of the Framework Agreement. The existing agreements that make up the Framework Agreement and the refund system are based on the use of mechanical recycling and the reuse of material. At the moment, chemical recycling falls outside the refund system. Given the fact that chemical recycling is recognised as a form of recycling, it is necessary to consider the possible position of chemical recycling within the refund system. To do so, the Packaging Waste Fund[55] must classify individual chemical recyclers as certified recyclers of plastics. The current fees follow a downward trend and are set until 2019. At the moment, the agreements of the Framework Agreement for Packaging are being evaluated. This presents opportunities to modify agreements in such a way that the chemical recycling of plastic packaging materials is also a viable option when this offers added value compared to current mechanical recycling techniques.

Stimulate the application of recyclate: modifications to food-safety regulations

Chemical recycling techniques are designed to break down plastics into their original building blocks (monomers) or even into basic raw materials for the chemical industry (syngas or naphtha) as much as possible. Furthermore, chemical recycling can be used to remove contaminants, additives and colourants from polymers. This cannot be done with mechanical recycling. Monomers are worth more on the market than basic raw materials. Additionally, monomers require fewer processing steps later on to convert them back into plastics. Several businesses are taking the initiative to develop chemical recycling processes, each focusing on their own technique or specific process. These techniques and processes differ in terms of how far they go in reducing the input stream to the original building blocks of plastics.

[55] This includes the executive organisations Nedvang and Verpakkingsketen B.V. (VPKT), which are involved in the collaboration and coordination with sorters and recyclers.

Given the fact that chemical recycling reduces the material to its original building blocks as much as possible and can be used to remove contaminants, it is expected to produce a raw material that can be used for similar purposes as virgin raw materials, for example for food-grade applications. The continued development of techniques and tests will help to further assess the possibilities in this regard. Regulations state that it must be possible to trace back 95% of the recycled packaging material that is reused for the production of packaging materials for food products to packaging materials for food[56]. When legal frameworks allow the recyclate from chemical recycling processes to be used for packaging materials for food products, this will increase the possible applications of the recyclate. It will likely also increase the demand for recycled plastics and result in more opportunities to develop circular packaging materials for food products.

In this regard, solvolysis and depolymerisation differ from pyrolysis and gasification. Because solvolysis and depolymerisation reduce the plastics to monomers and polymers, it must be demonstrated based on current food-safety regulations that food-grade applications for the recyclate fit within existing legislation. When the output of the pyrolysis or gasification of packaging waste is reused in the raw material chain in order to produce new packaging materials, the material has been broken down enough to make it comparable to virgin raw materials, so this is not a factor.

Stimulating the application of recyclate: CO_2 tax for virgin plastic to reduce the use of raw materials

A possible CO_2 tax for the production and/or use of virgin plastics will create a financial incentive to use more recyclate. This may also stimulate the further development of chemical recycling processes, since the growing demand for recycled plastics will also lead to a growing demand for (new) processing techniques for new applications. A different measure with which to realise the same effect is to incentivise the use of recycled (raw) materials (for example by reducing the VAT rate for recyclate).

Policy concerning biofuels affects options for the preservation of raw materials and the application of recyclate

The term chemical recycling covers various processes. Simply put, there are processes that produce monomers or polymers (depolymerisation and solvolysis processes). These output products can be used to produce products or packaging materials with limited additional effort. Furthermore, there are processes that produce a fuel or raw material (pyrolysis and gasification processes). These raw materials can be used to produce new chemicals or materials.

The European Union's policies specifically incentivise the use of biofuels for example for road traffic. The goal is to reduce the emission of greenhouse gases. Because the European Biofuels Directive from 2003 was not mandatory, insufficient progress was being made. To further stimulate the use of biofuels, the EU's Renewable Energy Directive (RED, 2009/28/EG) entered into force on 25 June 2009. This directive includes a higher and mandatory target of 10% for the use of biofuels for transport by

[56] When it comes to food safety, the European Union bases its legislation on recommendations from the European Food Safety Authority (EFSA). One of the guidelines of the EFSA – it must be possible to trace back at least 95% of the material in the recycling process to material that comes from the food industry – impedes the large-scale application of recycled plastics for plastic packaging materials for food products. With the exception of recycled PET from the deposit refund stream, other plastic streams cannot meet the EFSA's traceability requirements at the moment.

2020. There are proposals to include fuel produced from waste material in this directive as well, thereby classifying it as a biofuel. That is not the case at the moment. NGOs are especially critical of this. Dutch policies make use of HBE certificates to support the producers of biofuels. By late 2017, a certificate (equal to 1 gigajoule) had a value between €7 and €9. This policy is currently being revised with the goal of differentiating between different types of fuel in order to provide additional support to certain types of fuel.

It is currently unclear what the (European) policies of the future will be. The first point of attention for chemical recycling will be whether the European directive will actually classify products from waste-to-fuel processes as fuels under the RED. Europe can decide on this matter itself or leave it up to the individual member states. Especially for the techniques that produce a product that is close to a fuel, competition may arise between reusing the material as plastic (via waste-to-chemicals) and processing it into fuel (via waste-to-fuel), depending on the appeal of the (incentive) policy. In case of an appealing (Dutch) policy regarding the production of fuel from waste, “chemical recyclers” are more likely to produce such fuel. The tipping point depends on the origin of the waste material, among other things. Because there are no fees for processing waste from businesses (as opposed to domestic waste), this material is more likely to be used as fuel if the processing of waste into fuel is stimulated with policy measures. Furthermore, care must be taken to ensure that streams that could be processed via mechanical recycling are not processed via this process instead.

6.5 Measures and policy instruments that affect feedstock for chemical recycling other than packaging materials

Lastly, a number of (current) policy instruments and proposals will affect the available input for chemical recycling. The overview below is intended to provide insight into the possible effects, not a comprehensive picture of the situation.

The proposed increase of the incineration tax as an incentive for chemical recycling

The proposed increase of the incineration tax (Coalition Agreement Rutte III) benefits chemical recycling when it leads to a reduction of the volume of waste material that is incinerated. This leaves more material available for chemical recycling to produce new raw materials. Raising the incineration tax can also stimulate businesses’ waste separation rate and the processing of plastic packaging materials that are lost during sorting and recycling, due to the high(er) costs of incineration.

Weeelabex regulations result in more plastic input for chemical recycling processes

Weeelabex (Waste Electric and Electronic Equipment LABel of Excellence) is an initiative of European collection organisations for electric and electronic equipment, including Wecycle, who are united in the WEEE Forum. Weeelabex draws up uniform regulations for the collection, storage, transport, processing, recycling and reuse of e-waste. Independent auditors oversee compliance with these Weeelabex regulations and draws up a report on the volumes of material that were processed and the recycling results that were realised every year. The Netherlands was one of the first countries to adopt these regulations. They facilitate the regulated collection and processing of the material and result in more plastic input from electric and electronic equipment, which is (potentially) suitable for chemical recycling.

Expanding the manufacturer responsibility may lead to new plastic streams for chemical recycling

The Dutch government intends to expand the manufacturer responsibility to include for example clothing, furniture and (plastic) disposable products. Extending and expanding the manufacturer responsibility may challenge producers and retailers to only put products with a circular design on the market. To reduce the amount of litter, the option of extending the manufacturer responsibility to include disposable products that end up as plastic litter is being explored. The most common disposable products that end up as litter, besides packaging materials, are cigarette filters, chewing gum and balloons[57]. This policy proposal may lead to new plastic streams that are suitable for chemical recycling.

Import as a means to increase input

Streams that were previously exported from various (European) countries to China may possibly be used for chemical recycling in the Netherlands. Countries like Belgium, Germany and the United Kingdom may present import opportunities (stocks, losses and the mixed plastic stream). This appears to be possible within the existing legislative and regulatory frameworks. It should be noted that additional research into the legal and technical possibilities is needed, for example because the plastic streams must be comparable in terms of their composition.

EU proposal to tackle the problem of single-use plastics may limit the input for chemical recycling

The use of plastics is expected to increase further in the years to come. The EU's recent proposal to ban single-use plastics – or at least impose new rules regarding the use of the ten single-use plastic products that are most commonly found on Europe's beaches and in its seas (cutlery, plates, straws, etcetera) – may slow down the rate of this increase. However, given the relatively small volumes involved, this effect will be limited.

[57] See for example the Transition Agenda for Plastics, page 30:
https://www.rijksoverheid.nl/documenten/rapporten/2018/01/15/bijlage-3-transitieagenda-kunststoffen

Attachments

Attachment 1: The project approach used for "Chemical recycling of plastic packaging materials: analysis and opportunities for upscaling"

Chemical recycling is a collective term that is defined as follows in this report: using a chemical process to break down plastic material into its original building blocks – the polymers, monomers or atoms – which are then reused as raw materials in the manufacturing industry.

In this analysis, we distinguish between four techniques for the chemical recycling of plastics:

- Solvolysis (dissolution)
- Depolymerisation[58] (dissolution and heating)
- Pyrolysis[59] (heating)
- Gasification[60]

The four chemical recycling techniques examined in this analysis each have their own characteristics and they all involve different processes. Generally speaking, the techniques can be divided into relatively low-energy processes, which are suitable for the processing of relatively pure feedstock (solvolysis, depolymerisation), and high-energy processes, which are capable of processing input streams with a varied composition (pyrolysis, gasification).

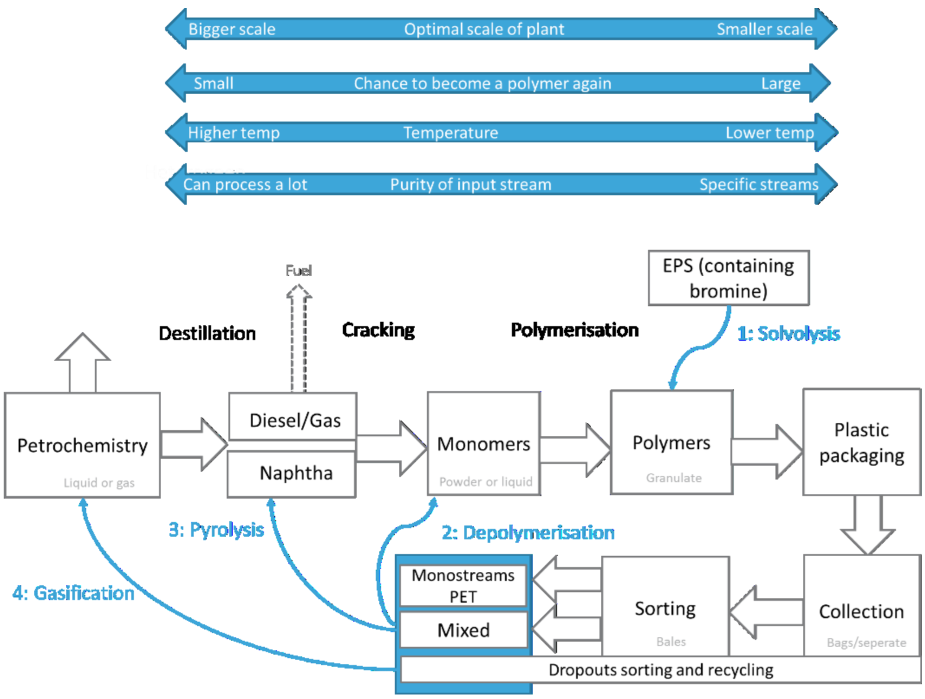

Image 8: A schematic overview of four demonstration processes for chemical recycling techniques, detailing the process steps involved, the requirements for the feedstock and the energy requirements.

58 Including magnetic depolymerisation
59 Including conventional techniques and integrated hydropyrolysis
60 Including low- and medium-temperature gasification

For the economic and environmental analyses, a demonstration process was modelled for each of the four techniques. Whenever possible, the input streams consist of plastic packaging materials that are currently not being recycled with mechanical techniques or which are mechanically recycled, but with only limited possible applications.

The principles used for the development of this analysis are the following:
- The exploration of the chemical recycling of plastic packaging materials stems from the need for waste processing capacity and the expanded recycling ambitions for plastics. The analysis therefore focuses on the chemical recycling of plastic packaging streams that are not yet being recycled with mechanical techniques.
- Recycling plastic packaging materials with mechanical techniques is preferable because it results in the shortest circularity cycle. We therefore consider the use of chemical recycling in addition to mechanical recycling: mechanical recycling techniques for plastic packaging materials are used whenever possible, while chemical recycling techniques for plastic packaging materials are used where necessary. In the long run, chemical recycling techniques may replace mechanical recycling techniques because market effects have a more significant impact, for example due to a growing demand for recycled raw materials that are suitable for food- or high-grade applications.
- In this analysis, we employ the definition of chemical recycling that is used in LAP3: a process is classified as "recycling" when its output is reused as raw material for the manufacturing industry.
- The current composition of sorted plastic packaging waste streams or sorting and recycling losses is maintained.

Foundations for the conclusions and measures for upscaling
To develop measures for the upscaling of the chemical recycling of plastic packaging materials, economic and environmental analyses were conducted based on research from CE Delft and TNO. The insights and data acquired with this research form the foundation for the conclusions and measures in this report.

1. Exploration of promising input streams for the chemical recycling of plastic. This analysis focuses on the streams of plastic packaging waste that appear promising for chemical recycling, either because they are currently not being recycled mechanically or because the output of mechanical recycling offers limited application opportunities. The volumes of promising input streams for chemical recycling and the scenarios for the expansion of these input streams by 2030 are based on the research that CE Delft conducted to calculate the environmental effects of chemical recycling[61]. The promising streams of plastic packaging waste are described in chapter 4.4.
2. Exploration of the potential opportunities that the chemical recycling of plastic packaging waste presents for the Netherlands. How can investments in or subsidies for chemical recycling be made economically viable in the long run and contribute to the improvement of

[61] An exploration of the environmental effects of chemical recycling was conducted by CE Delft by order of the Ministry of Economic Affairs and Climate Policy. By order of the KIDV, this study was expanded with information about available streams and techniques for the purposes of this analysis.

the Netherlands' economic or knowledge position? The opportunities that chemical recycling can offer in the Netherlands are outlined in chapter 3 of this analysis.

3. CE Delft has assessed the environmental effects of the four aforementioned techniques. Among other things, the energy requirements of the process steps and the output of each chemical recycling technique were expressed in CO_2 equivalents per ton. The environmental effects of chemical recycling are compared to those of the processing technique that is currently being used for the input stream in question. Chapter 5 covers the environmental impact of each of the four chemical recycling techniques.
4. An analysis of the process costs of the four techniques. TNO[62] has calculated the process costs of each technique at the generic level by modelling the capital costs, process steps, costs of the input streams and sales prices for the output streams. The process costs are based on the likely process scales, considering the available input streams, as outlined in CE Delft's exploration of the environmental effects of chemical recycling.[63] The process costs of each technique are covered in chapter 5.
5. Chapter 6 outlines the restrictions and opportunities for chemical recycling in current policies and regulations.

The overview below shows the connections between the initiatives and studies conducted by TNO, CE Delft and the KIDV.

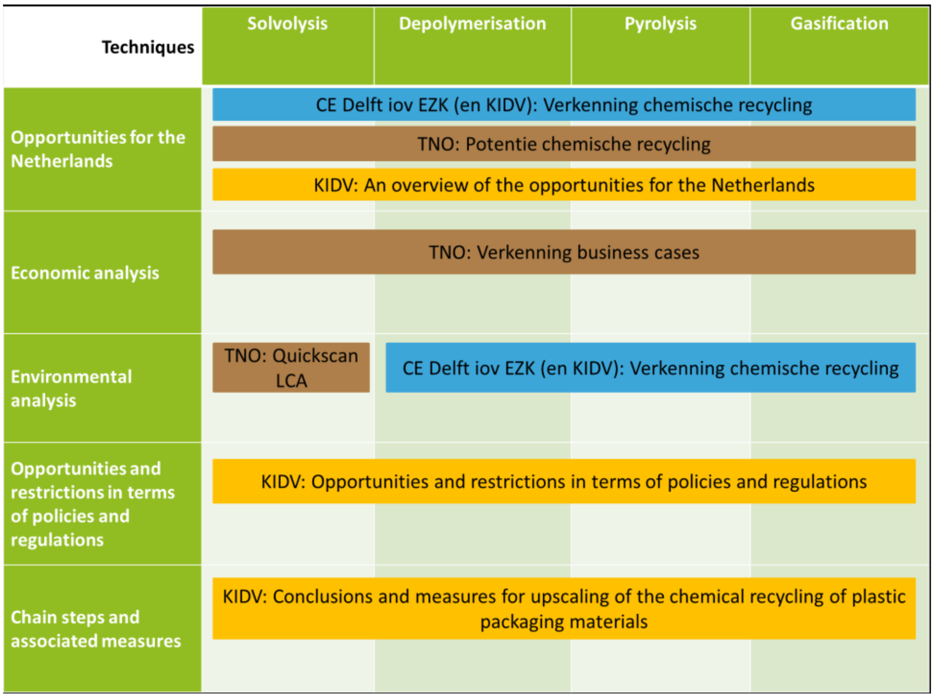

Image 7: Analyses conducted within the context of the project in order to develop the conclusions and measures for upscaling.

[62] An analysis of the production costs and gross profits of four chemical recycling processes, TNO by order of the KIDV, October 2018.

[63] An exploration of chemical recycling, CE Delft, September 2018

Attachment 2: Goal and motivation for this analysis

Why analyse the chemical recycling of plastic packaging materials?
Although the collection and mechanical recycling of plastic packaging waste have grown significantly in recent years, the market for recycled plastic still faces many challenges. In addition to existing recycling techniques, research is being conducted to develop alternative or additional techniques to improve and increase the recycling of plastic packaging materials, optimise the quality of the recyclate and create more application opportunities. Chemical recycling is one of these techniques. It offers a number of advantages compared to mechanical recycling.

In the KIDV's Plastic Chain Project, scaling up the chemical recycling of plastic packaging materials from the pilot scale to an industrial scale was identified as a system change that will have a major impact on the further closing of the plastic packaging chain. The Transition Agenda for Plastics includes the ambition to realise an annual output of 250 kt from chemical recycling by 2030, in addition to the mechanical recycling of plastic products and packaging materials.

In this analysis, we describe the measures that have to be taken and the conditions that have to be met in order to scale up the chemical recycling of plastic packaging materials. Furthermore, this analysis was drawn up to provide insight into the opportunities, legal restrictions and (im)possibilities of chemical recycling techniques, their environmental impact and associated costs. The analysis is intended to offer stakeholders in the waste management and recycling sector insight into the role that chemical recycling can play in the processing of plastic packaging materials into raw materials with many possible applications. Furthermore, the conclusions and measures for upscaling outlined in this report provide insight into the considerations that have to be made and the measures that have to be implemented.

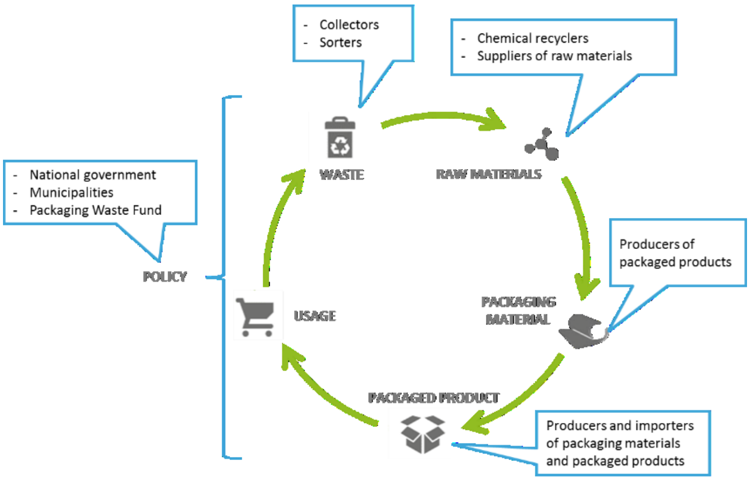

Image 8: Target audiences of this analysis and associated measures.

Attachment 3: Support and reflection

Sounding board group

To create support for and reflect on the results described in "Chemical recycling of plastic packaging materials: analysis and opportunities for upscaling," a comprehensive sounding board group got together on three occasions. The sounding board group consists of the various stakeholders from the plastic packaging chain, the chemical industry and the national government. The (interim) results of TNO and CE Delft's studies of the process costs and environmental impact of the various chemical recycling techniques and the principles of this report were also assessed by the sounding board group. It consists of the following members:

- The Ministry of Infrastructure and Water Management
- The Ministry of Economic Affairs and Climate Policy
- FNLI
- NRK
- Plastics Europe NL
- VNO-NCW
- Port of Rotterdam
- Natuur & Milieu Foundation
- VNCI

Board of Independent Experts (BoIE)

A concept version of "Chemical recycling of plastic packaging materials: analysis and opportunities for upscaling" was presented to the KIDV's BoIE on 11 September 2018. The board offered its reflections and substantive commentary on the report and the analysis. The input from the members of the BoIE was incorporated into the final version of the report. The BoIE consists of the following members:

- Jacqueline Cramer
- Jan Paul van Soest
- Roland ten Klooster
- Jos Keurentjes
- Peter Rem