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CHEMICAL PLASTICS RECYCLING – POTENTIALS AND DEVELOPMENT PROSPECTS

A contribution to defossiling the chemical and plastics processing industry in NRW

Discussion paper by the Circular Economy Working Group

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Authors: Dr Stephan Ramesohl (Wuppertal Institute), Laura Vetter (Wuppertal Institute), Raoul Meys (RWTH Aachen), Sören Steger (Wuppertal Institute)

Contributors: Dr Philipp Bendix (Wuppertal Institute), Dr Bernd Kaletta (Lanxess), Dr Georg Kobiela (Wuppertal Institute), Julia Koop (Rain Carbon), Dr Ulrich Seifert (Fraunhofer UMSICHT), Dr Christoph Sievering (Covestro), Ph.D. Balint Simon (RWTH Aachen)

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Coordination: Dr Lukas John, Iris Rieth (IN4climate.NRW)
Contact: lukas.john@in4climate.nrw, iris.rieth@in4climate.nrw

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OUR KEY MESSAGES

As an exploitation route for mixed plastic waste, pyrolysis is a forward-looking process that can contribute to shaping a climate-friendly chemical industry.

- The technical principles of plastic pyrolysis are available.
- Input materials are available for chemical recycling in NRW.
- A climate policy perspective on chemical recycling is emerging.
- There is a need for development, especially regarding the recycling of mixed plastic waste.

This discussion paper calls for the following in-depth studies to further develop the procedure:

- An **in-depth technology assessment** with an evaluation of existing development work and a more targeted description of reaction technology parameters to determine a specific development requirement.
- An **analysis of political and market conditions,** also in light of foreseeable trends and acceptance.
- An in-depth **scenario analysis of future plastic waste streams** to stimulate long-term investments and to estimate the future potential of chemical recycling.
- An in-depth **ecological and economic evaluation of pyrolysis product**s both for the current situation and forecasted for 2030 and 2050.
- Development of the **“Chemisches Kunststoffrecycling NRW”** (NRW Chemical plastics recycling) strategic roadmap.
- Conducting a **cooperative follow-up study by industry and science** with the goal of elaborating on and assessing the strategic perspective of a demonstration plant for thermochemical plastic waste recycling in NRW as a contribution to ecological structural change in the state.

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1. BACKGROUND, TASKS AND OBJECTIVES

In the Paris Agreement, national and international stakeholders set the goal of limiting global warming to 1.5 degrees Celsius. This essentially means defossiling the economy and society by the middle of the century and extensively converting the energy supply to carbon-free, renewable energy sources.

The chemical and plastics industries are faced with a particular challenge regarding their responsibility to protect the climate in that fossil fuels such as oil and natural gas are currently not only used as fuels, but are also the main source of carbon for material use (non-energy consumption). Because of this, the industry has to play the double role of reducing energy and process-related greenhouse gas emissions as well as switching to a climate-friendly raw material base and utilisation.

Figure 1 illustrates the current situation, whereby the production of plastics is based on petrochemical raw materials derived from processing crude oil at refineries. These refineries predominantly focus on supplying the transportation industry with fuels (as well as heating fuels to a lesser extent, e. g. in the heating market). As part of effective climate protection strategies for the transportation sector, the use of these fossil fuel resources must be gradually reduced and alternative renewable energy sources must be developed. In the future, refineries and petrochemical companies will become less important as the raw material base for the plastics industry. As a result, alternative carbon inputs will have to be developed as a resource.

Considering the very limited global potential of sustainable biomass production, there are two main strategy options (see Figure 1):

- increased recycling and reuse of the carbon bound in plastic products through increased recycling (material and chemical)
- from a broader perspective, industrial synthesis of hydrocarbons using regenerative hydrogen and climate-neutral CO_2 sources (e. g. through direct air capture processes or recycling CO_2) or unavoidable CO_2 emissions from industrial processes

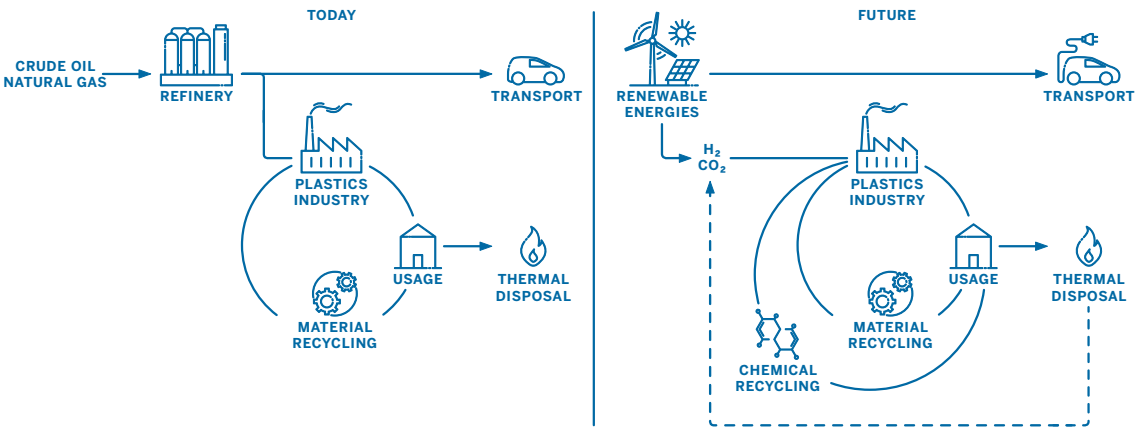

Figure 1: Illustrative representation of the carbon cycles in the plastic system.

The discussion paper by the Circular Economy Working Group focuses on the first strategy option for future carbon recycling. Currently, smaller proportions of the plastics accruing after the use phase are already being recovered through mechanical recycling, but the majority is recovered thermally (see Chapter 6.1). In the future, it will be necessary to cut back on thermal recycling and reduce it to technically unavoidable losses in order to significantly increase the proportion of material reuse and open up additional environmentally sound recycling options. Chemical recycling processes offer a previously untapped option.

The work of the Circular Economy Working Group is understood as a primary, preparatory concept phase to explore and determine the limitations of possible courses of action for chemical recycling, which can be expanded in terms of content and methodology in a possible subsequent phase. In the context of the IN4climate.NRW initiative, this can lay the foundation for tangible, industry-supported development projects. Over the medium to long term, successful development work could lead to the demonstration and establishment of a cluster called "Circular Plastics Industry NRW" (working title).

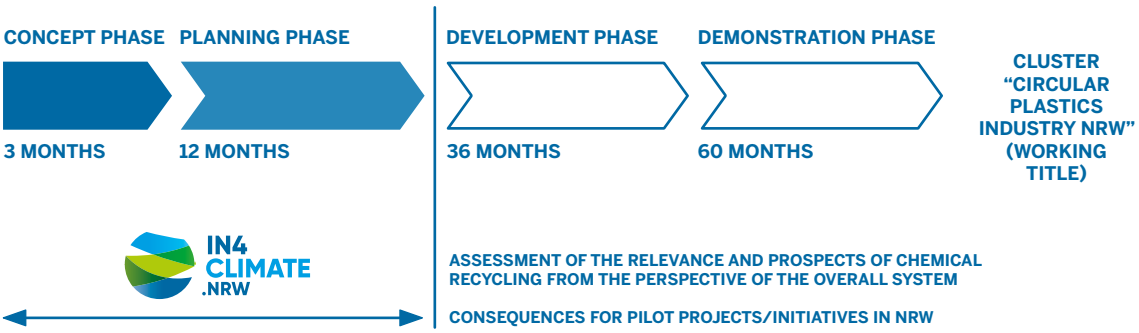

Figure 2: Classification and context of the concept phase of the Circular Economy Working Group.

The aim of this discussion paper is therefore to

- outline the potential and development prospects of the chemical recycling of plastic waste as a contribution to defossiling the chemical and plastics processing industry in NRW,
- describe essential technology routes and options and assess the current state of technology (Chapter 3 and Chapter 4),
- assess initial ecological effects and benefits (Chapter 5),
- outline possible mass flows, quantity structures and market conditions (Chapter 6),
- identify open questions and additional research needs that provide the basis and framework for further work (Chapter 7).

The reference framework for the study is a holistic understanding of the changes in energy and industrial systems and their consequences for the ecological-economical evaluation of courses of action.

2. LIMITATIONS, WORKING HYPOTHESES AND ANALYTICAL APPROACH

Various concepts and processes are available for recycling plastic waste. Their applicability and effective contributions to climate and resource protection depend heavily on the quality and material composition of the waste streams (see Chapter 3.1).

This discussion paper examines previously untapped process routes for the chemical recycling of mixed plastic waste in NRW (see overview in Chapter 3.1). The discussion focuses on the specific question of whether and to what extent developing and advancing pyrolysis technologies offers the potential for environmentally sound recycling of mixed plastic waste and recycling of the carbon bound in the plastic.

This limitation is based on the following working hypotheses:

- In order for recycling processes to achieve the greatest possible contribution to climate and resource protection, attempts should be made to maintain the material composition and polymer structures and thus the economic-energetic value of the plastics and to minimise the energy input to recycle (sorting, decomposition and synthesis) the compounds used.
- Material recycling should therefore be pursued for many types of plastics, such as thermoplastics. This, however, requires corresponding homogeneity and cleanliness in the sorting and preparation processes (e. g. deposit systems for PET bottles). Product and packaging design measures, optimising separation behaviour and collection logistics and new sorting and processing technologies will increase the proportion of recyclable plastics overall.
- For specific types and qualities of plastics, depolymerisation processes also offer the possibility of recycling at a high material level if they are collected by type (e. g. by the respective manufacturers).
- For large parts of the waste streams, however, single-sort collection or processing is currently not available and substantial quantities of mixed plastic waste will continue to be generated in the future.
- Currently, these quantities are thermally exploited (substitute fuel or waste incineration), during which the carbon bound in the material is lost. Gasification processes fundamentally offer an additional option for the treatment of mixed waste, but the synthesis gas only contains the basic building blocks, namely H_2 and CO, which makes subsequent material use very costly.
- Pyrolysis processes, however, can produce a wider range of products with longer chain compounds based on the type of process and operation, which are advantageous for material use in downstream chemical processes.

The study therefore concentrates on the **potential of pyrolysis technologies for recycling mixed plastic waste** that is not suitable for high-grade mechanical or chemical recycling (depolymerisation) (see Figure 3). The different manufacturer-specific approaches to and initiatives for recycling specific product groups are therefore not included in the present analysis, but are supplemented by the rather broadly chosen approach of pyrolysis.

A need for investigation can be seen in the chosen topic area, since previous approaches to pyrolysis are mostly oriented towards the production of cracker feedstocks for the petrochemical network (see Chapter 4.1) and therefore tend to be susceptible to impurities and contaminants. In this discussion paper, it is assumed that adapted technology configurations (and possibly those yet to be developed) have higher tolerances against impurities, especially inorganic impurities, from mixed plastic waste and can provide an attractive product spectrum for chemical processes. Similar opportunities exist for the recycling of engineering plastics, although their suitability must be considered separately in each case due to the large variety of materials and their very specific compositions (including additives etc.).

The reference point for the environmental assessment (see Chapter 5) is the substitution relationship with thermal recovery as refuse-derived fuel (RDF) or waste incineration (WIP).

In the context of the changed system environment and decarbonisation of the energy system outlined above (in particular the expansion of carbon-free power generation), a trend towards declining CO_2 credits from the thermal disposal of plastics is assumed.

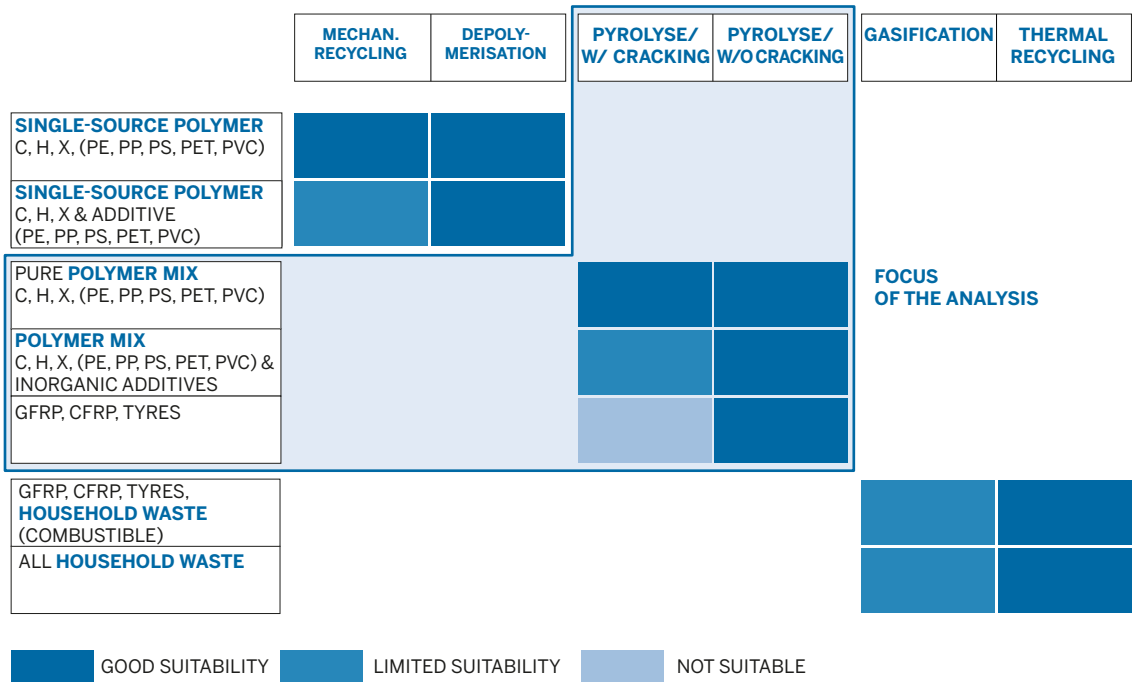

Figure 3: Definition of the research subject – an analysis focused on pyrolysis of mixed plastic waste.

3. TECHNOLOGY OVERVIEW

It is apparent from the previous chapters that there are different options and process routes for recycling plastic waste. This chapter presents a technology overview of chemical recycling, providing the working basis for this discussion paper. The focus is on pyrolysis, the main technology considered in this study.

The following key points and questions are clarified:

- How do we classify pyrolysis technology in the context of chemical recycling?
- What technologies are discussed in the context of chemical recycling? How can we define these technologies and what working concepts/terminology are used in the discussion paper?
- How can we classify pyrolysis processes?

Basic definitions of terms are discussed in Chapter 3.1 and a graphic summary and overview of the subject area of chemical recycling, especially pyrolysis is shown in Chapter 3.2.

3.1 Definition of terms

A common feature of the processes considered in this discussion paper is the thermal decomposition (thermochemical conversion) of higher molecular weight substances to lower molecular weight reaction products at an elevated temperature. This excludes processes that lead to complete oxidation (combustion) of the starting material.

In the literature, various technical terms are used for processes with the same process characteristics (described in more detail in Appendix 9.2) and can therefore be used interchangeably or have identical meanings in process technology.

Some terms are also defined and used differently in the literature and thus partly contradict each other. This problem is also described in a report commissioned by the EU titled “A circular economy for plastics: insights from research and innovation to inform policy and funding decisions” by Crippa et al. (2019).

It is therefore crucial to clarify and define terms to establish a common working basis. For this reason, selected terms used in the context of chemical recycling are explained or defined in more detail below.

This is particularly relevant if the “eligibility” or “non-eligibility” of recycling rates is determined in a regulatory context by choosing a certain term.

- **Chemical recycling** is an umbrella term for processes that use more than just mechanical or physical processes to prepare the starting material but do not lead to complete chemical conversion (combustion) with atmospheric oxygen.
- **Tertiary recycling** is a less common synonym for chemical recycling.
- **Feedstock recycling/raw material recycling** is a process that converts the starting material into chemical feedstock (e. g. for synthesising). This includes the thermochemical processes considered below.

- **Depolymerisation** is the process of splitting a polymer into monomers or oligomers, i. e. short-chain polymer units.
    - **Chemical depolymerisation** is depolymerisation by "chemical attack", e. g. hydrolysis.
    - **Solvolysis** is a special form of chemical depolymerisation applicable for polycondensates (e. g. polyester, polyamides), especially in hydrolysis (bond splitting using water as a reactant). However, this term is often used interchangeably with chemical depolymerisation in the literature. Different solvents may be used. In this respect, solvolysis can be further divided into glycolysis, methanolysis, hydrolysis and aminolysis.
    - **Chemolysis,** according to the elements of the word, means splitting (lysis) a compound using chemical agents; the wording is very general. The term is usually used interchangeably with solvolysis in the literature.
    - **Thermal depolymerisation** describes depolymerisation by energy supply at elevated temperature. It is currently used for PMMA and to a certain extent for polystyrene. In that case it is a variant of pyrolysis.

Definition of thermochemical processes to recycle plastic waste

The term "process" is itself ambiguous: It can stand for the application of certain process engineering principles (temperature, auxiliary materials or target products of decomposition, as explained in more detail in Appendix 9.2), but it can also be mean a defined combination of process steps and apparatus under certain process conditions (such as the Haber-Bosch process for ammonia synthesis).

This ambiguity also explains why different classifications can sometimes be found in the literature for the same procedural term.

Technical process designations substantiate individual process characteristics:

- **Pyrolysis:** allothermal (with external energy supply) process excluding oxygen and air.
- **Catalytic cracking:** allothermal catalytic process.
- **Hydrocracking:** allothermal, catalytic process with the addition of hydrogen.
- **Gasification:** autothermal process (without external energy supply) by partial oxidtion using an additional gaseous reactant.
- **Reforming:** Depending on the application context, different processes meaning "chemical transformation". A liquid hydrocarbon fraction (naphtha or pyrolysis oil) is usually used as the starting material.

In reference to Lechleitner et al. (2019), the cited thermochemical processes can be further characterized as follows:

- **Pyrolysis:** thermochemical process by which polymers are split at temperatures above 300 degrees Celsius, resulting in a wide range of products. This happens through a radical chain splitting mechanism. Depending on the process conditions, pyrolysis gas, synthetic crude oil/pyrolysis oil and pyrolysis waxes are produced. These can be further processed through distillation and refining steps to produce higher-value chemicals such as monomer units for polymer chemistry or basic chemicals and fuels. These treatment steps can be integrated into the process or carried out downstream in a conventional refinery.

- **Catalytic cracking:** thermochemical process. This process utilises an additional catalyst compared to pyrolysis. This reduces the activation energy of the chain splitting reaction and influences the product spectrum. More branched, ring-shaped and aromatic compounds are formed compared to purely thermal degradation. Heteroatoms such as nitrogen, oxygen and sulphur can have a problematic effect on the process because they can act as catalyst poisons.

- **Hydrocracking:** thermochemical process. In comparison to pyrolysis, hydrogen is also added at partial pressures of 2 to 15 MPa, often in the presence of a bifunctional catalyst. Due to the availability of hydrogen, mainly saturated and less unsaturated and aromatic hydrocarbon compounds are formed. The process can also be carried out in two stages with upstream pyrolysis and downstream hydrogenation. This offers the advantage of removing heteroatoms, impurities and coke in an intermediate step after pyrolysis to protect the catalyst.

- **Gasification:** partial oxidation using air, oxygen, steam or mixtures of hydrocarbons, usually at temperatures of between 700 and 1,600 degrees Celsius and pressures of between 10 and 90 bar. Depending on process conditions and feedstock, the product gas contains CO, H_2 and even CH_4 as well as higher hydrocarbons, possibly with heteroatoms. This is an autothermal reaction; the exothermic partial reactions release energy which feeds the partial reactions and leads to energy absorption. As a result, the process requires no external energy supply. Subsequent gas purification is important because the downstream processes are predominantly catalytic and therefore sensitive to impurities.

- **Catalytic reforming of naphtha/pyrolysis oil:** The objective of the process is to convert aromatic compounds. Four reactions take place during the process: dehydrogenation of cycloalkanes to aromatics, dehydrocyclisation of paraffins to aromatics, isomerisation and hydrocracking of alkanes to branched or short-chain alkanes (Speight 2010).

Distinction between cracking and pyrolysis

The term "cracking" is mainly used in the petrochemical industry where it is preferred over the term "pyrolysis". From a purely procedural perspective, both terms mean anaerobic allothermal processes and have the common goal of breaking down polymer chains into shorter hydrocarbon components. There is no difference between the procedures in this respect. The same applies to the following terms:

- Thermal cracking
- Thermal decomposition
- Pyrolytic cracking
- Thermolysis

A tabular comparison of the advantages and disadvantages of the various chemical plastics recycling processes can be found in Appendix 9.3.

3.2 Working term 'pyrolysis' and overview of "chemical recycling"

In the following discussion paper, the **working term 'pyrolysis' i**s used as defined in Chapter 3.1. A graphic classification and overview of the terms defined in Chapter 3.1 is provided in Figure 4, including the various circuits for plastics in a recycling economy. This is based on the type of change in the polymer structure as a classification characteristic for the respective recycling path. Pyrolysis can be classified as such (as well as based on the definitions in Chapter 3.1) both under feedstock recycling and, in special cases, under depolymerisation (see thermal depolymerisation).

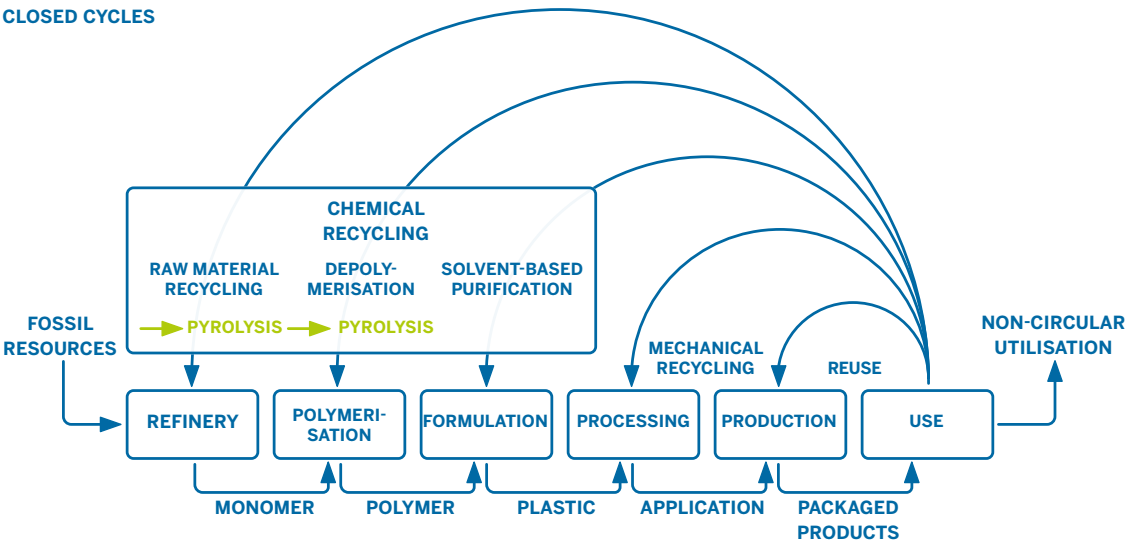

Figure 4: Overview of different cycles for plastics in a recycling economy. Modified according to Crippa et al. 2019.[1]

[1] "Since solvent-based cleaning does not change the composition of the polymer itself, it is argued that it should be considered mechanical rather than chemical recycling or a separate class (see also ISO 15270:2008). This report does not promote one option over another. The logic applied here is that chemicals used in solvent-based cleaning to change the formulation of the plastic (by removing additives and extracting the base polymers) can be described as one of several chemical recycling techniques. Note that this positioning of solvent-based cleaning is for practical purposes and is not a recommendation for standardised terminology." (Crippa et al. 2019)

4. ASSESSMENT OF THE STATE OF TECHNOLOGY AND BASIC FEASIBILITY

This chapter describes previous activities and the state of technology for pyrolysis processes in order to comment on the feasibility of applications of the technology for the recycling of mixed plastic waste as a contribution to defossiling the chemical and plastics processing industry. The following key points and questions are examined:

- What stage of development are pyrolysis processes for plastics recycling at based on the literature?
- What experiences and results have been gathered to date and what open questions are discussed or result from them?
- What are the next development tasks and steps?

Chapter 4.1 provides an overview of the state of development of the pyrolysis technology. The results of the evaluation of scientific review articles are presented in Chapter 4.1.1 and current industrial projects are described in Chapter 4.1.2. Following this, Chapter 4.2 discusses some of the key results and findings on the state of development of plastics recycling by pyrolysis.

4.1 Literature overview on the state of research and development of pyrolysis technologies

A literature review was carried out to estimate the state of research and development of the pyrolysis technology for the recycling of mixed plastic waste. Scientific review articles are evaluated in Chapter 4.1.1 and sources on current industry initiatives in Chapter 4.1.2. Gasification processes are also considered in Chapter 4.1.1 to enable a comparison with large-scale waste recovery processes. The results of both research projects are presented graphically in Figure 5.

4.1.1 Literature overview from scientific review articles

Six review articles (Lopez et al. 2017; Lopez et al. 2018; Singh et al. 2017; Stapf et al. 2018; Thunman et al. 2019; Anuar Sharuddin et al. 2016) on thermochemical processes for the recovery of plastic waste were found and used to prepare an overview.

These contain a total of 174 references describing processes that can be subdivided according to technology, technology readiness level[2] (TRL) and input stream. These are depicted as an over-view chart in Figure 5. Laboratory scale procedures (TRL <6) have been summarised and illustrated. Processes that are already ready for demonstration or commercialisation have also been summarised in Table 1.

[2] Since the technology readiness level is only explicitly stated in one publication, it was estimated for the others based on throughput. (TRL 4: <4kg/h; TRL 5: over 4kg/h; TRL 6 over 10 kg/h; TRL 7 over 60 kg/h; TRL 8 over 400 kg/h). An overview of the classification according to TRL can be found in Appendix 9.1.

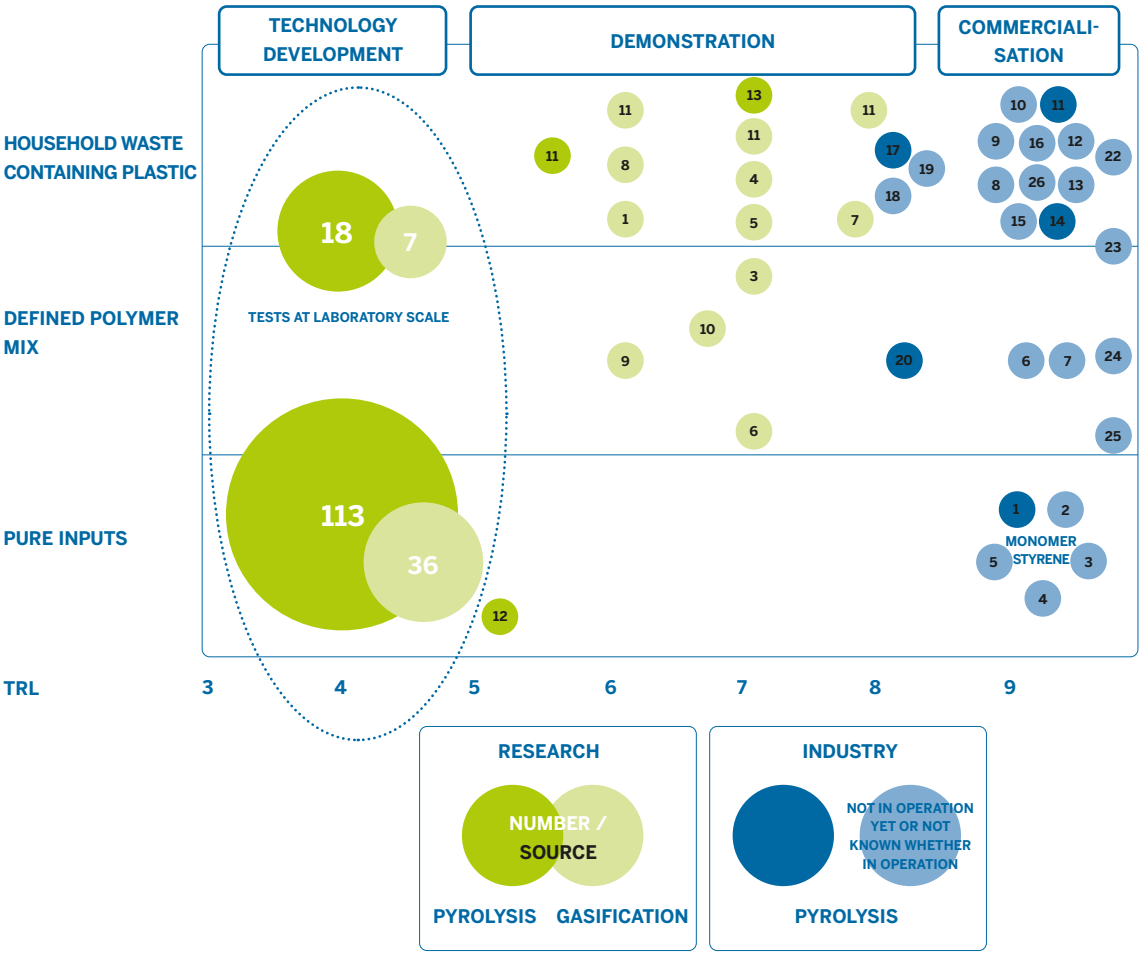

Figure 5: Overview of selected results of the literature search. The sources for the referenced numbers can be found for research results in Table 1, for industrial projects in Table 2.

Table 1: Literature references for processes from the review articles with TRL ≥6 (* TRL estimated, see above).

No.	Source	TRL	Rate [kg/h]	Process	Reactor Configuration	Input	Producte
1	Wilk, V./Hofbauer, H. (2013 b)	6*	7,5 - 16,6	Gasification	Double Fluidised bed	Mixed plastic waste	Monomer recycling
2	Tukker, A. et al. (1999)	7 - 8*	200 - 400	No data	Double Fluidised bed	PVC resins	HCl and combustible gas
3	Maric, J. et al. (2018)	7 - 8	370	Gasification	Double Fluidised bed	Automotive shredder residue	Monomer recycling
4	Arena, U./Di Gregorio, F. (2014)	7*	100	Gasification	Fluidised bed	Mixed plastic waste (mainly PE)	No data
5	Arena, U. et al. (2010)	7*	100	Gasification	Fluidised bed	Mixed plastic waste	No data
6	Arena, U./Di Gregorio, F. (2016)	7*	100	Gasification	Fluidised bed	Biomass	No data
7	Lee, J. W. et al. (2013)	7*	80	Gasification	pilot-scale moving-grate	Mixed plastic waste	H_2, CO, CO_2, CH_4 for power generation
8	Wilk, V./Hofbauer, H. (2013 a)	6*	15	Carbon gasification	Double Fluidised bed	Wood pellets / plastics from MSW	H_2, CO, CO_2, CH_4
9	Kern, S. J. et al. (2013)	6*	15	Carbon gasification	Double Fluidised bed	Lignite / PE	H_2, CO, CO_2, CH_5
10	Ponzio, A. et al. (2006)	6 - 7*	60	Carbon gasification	Updraft	Polyolefin waste / biomass	H_2, CO, CO_2, CH_6
11	Stapf, D. (2018)	6 - 9	No data	Gasification	Fixed bed, Fluidised bed, entrained flow	Plastic house-hold waste	Synthesis gas for methanol synthesis
		5 - 6	No data	Pyrolysis	No data		Pyrolysis oil for steam crackers
12	Miskolczi, N. et al. (2009)	5*	9	Pyrolysis	Horizontal tube reactor	HDPE/PE	Pyrolysis oil, gas, wax, coke
13	iCAREPLAST (2019)	7	>100	Pyrolysis (catalytic)	No data	Mixed plastic waste	Pyrolysis oil (aro-matics), coke, liquid CO_2

Results of the literature evaluation of research papers

The evaluation shows that the state of research is concentrated on the laboratory scale and that mainly pure substances were used as input material.

Of the 133 pyrolysis processes, only two are depicted on a pilot scale. The remaining 131 are on a laboratory scale. Relatively speaking, gasification is somewhat further developed, but large-scale processes are also limited. From the sources considered for gasification, there are ten processes with a technology readiness of TRL ≥6 and 41 processes on a laboratory scale.

Additionally, 150 out of 174 sources use pure substances as feedstock (pyrolysis and gasification considered together). Defined plastic mixtures are found in many of these sources, and contaminated mixed plastic waste is only found in a few. The feedstock for the larger-scale processes are listed in Table 1.

It can be concluded from the overview of the technology readiness of pyrolysis that there is still a considerable need for research and development in the application of chemical recycling of mixed plastic waste.

This result is confirmed by Stapf et al. (2018) and Lopez et al. (2017), who refer to the need to develop pyrolysis (and gasification) processes.

The EU project iCAREPLAST (Integrated Catalytic Recycling of Plastic Residues into Added-Value Chemicals), launched in 2018, aims to close this research gap and implement a process for cost-effective and energy-efficient recycling of currently non-recyclable plastics and composite materials. It is scheduled to run for 48 months with funding of 6.51 million euros involving ten partners from five European countries. The Spanish research institution Agencia Estatal Consejo Superior de Investigaciones Científicas is managing the project. The project involves an integrated process consisting of catalytic pyrolysis, catalytic post-treatment (alkylation and hydrotreatment) and a membrane separation process. Waste sorting and pretreatment occurs upstream. Benzene, toluene and xylene (BTX) as well as other alkyl aromatics and liquid CO_2 will be produced. The plant will have a capacity of more than 100 kilograms of plastic per hour (~900 t/a, TRL-7) (iCAREPLAST 2019).

4.1.2 Overview of industrial initiatives to demonstrate and commercialise pyrolysis technologies

Research results on current commercialisation approaches for pyrolysis technologies to recycle plastic waste are summarised in Table 2. In addition to pyrolysis, depolymerisation processes are also presented in the lower part of the table.

For greater clarity, the industry initiatives in Table 2 are presented along with the results from Chapter 4.1.1 in the overview chart shown above as Figure 5. It can be concluded from the summary that there are a number of activities and great interest in the chemical recycling industry. Some companies have apparently already successfully commercialised raw material recycling for plastics using pyrolysis technology and many are on the brink of doing so.

The Plastic Energy and Pyrum Innovation companies are already on the market with their pyrolysis processes for recycling plastic waste. As far as can be seen from the existing research results, over 10,000 tonnes of this waste are produced per year. Little information can be derived from the literature about the requirements for the input stream, the composition of mixtures of different plastic types, or how much contamination is permissible by certain impurities. In addition to these two larger facilities, the OMV Group operates a pilot-scale pyrolysis plant for polyolefins. This is affiliated with the Schwechat Refinery. BASF has developed and commissioned a prototype for unsorted, mixed and contaminated plastics.

Many industry initiatives have also announced the commercialisation of quite large facilities. The largest projects are planned as a joint venture between Gas Technology Institute (Illinois), CRI Catalysts and Shell with a capacity of 700,000 tonnes per year, followed by Plastic Energy with 200,000 tonnes per year and Brightmark Energy with 100,000 tonnes per year. Quantafuel is already in the process of building a facility with a capacity of 18,000 tonnes per year. BASF recently invested 20 million euros in the Norwegian company to jointly promote the chemical recycling of mixed plastic waste (Stark 2019).

Agilyx claims to have the world's first commercial pyrolysis plant in Tigard, Oregon (Agilyx 2018) for the chemical recycling of polystyrene to its monomer styrene. The company plans to open three new facilities in the coming months (Tullo 2019). It has also sold its technology to three companies in the United States (Agilyx 2019a), including polystyrene producer Ineos Styrolution.

Many of the initiatives mentioned are based on joint ventures between companies along the value chain (raw material suppliers and buyers of the products) and adapting the products to their specific requirements.

The initiatives mentioned above and other industry initiatives can be found in Table 2 with further information. It can be concluded from the summary that there are obviously a number of activities and substantial interest in the chemical recycling industry and increased development can be expected in the coming years.

Table 2: Overview of current and planned industrial initiatives to exhibit and commercialize pyrolysis technologies and depolymerization.

No.	Company	Plant			Capacity	Input	Product(s)	Buyer	Reference
		Procedure, Process	Location	Commissioning					
1	**Agilyx joint venture with Americas Styrenics (AmSty)**	Pyrolysis of PS	Tigard, Oregon, US	April 2018	3,650 t/a	PS	Styrene	Styrene and polystyrene manufacturers AmSty and INEOS Styreneution to be processed for the manufacture of consumer goods	Agilyx 2018; Agilyx 2019
2	**INEOS Styreneution (with Agilyx Tecnologie)**	Pyrolysis of PS	Channahon, Illinois, US	In planning, no further information	36,500 t/a	PS	Styrene	INEOS Styreneution as a PS manufacturer itself	Tullo 2019
3	**Agilyx joint venture with Americas Styrenics (AmSty)**	Pyrolysis of PS	Western US	In planning, no further information	18,000 t/a	PS	Styrene	Styrene and polystyrene manufacturers AmSty and INEOS Styrolution to be processed for the manufacture of consumer goods	Tullo 2019
4	**Trinseo and INEOS Styreneution (with Agilyx Technologie)**	Pyrolysis of PS	Europe	In planning, no further information	18,000 t/a	PS	Styrene	INEOS Styrolution and Trinseo (Luxmburg chemical concern) as PS manufacturer itself	Tullo 2019; Kunststoff-Web 2019; Trinseo 2019
5	**INEOS Styreneution with Indaver**	Pyrolysis of PS	Mechelen, Belgium	In planning, no further information	No data	PS	Styrene	Partnership with food packaging group Sirap	Kunststoff-Web 2019; William and Burridge 2019
6	**BlueAlp**	Pyrolysis, BlueAlpTM Technology	No data	No data	20,000 t/a	Polyolefin	No data	No data	BlueAlp 2019; Petrogas 2019
7	**Clariter**	Pyrolysis	No data	No data	10,000 t/a	PE, PP, PS	No data	No data	Clariter-global clean-tech group 2019
8	**Illinois-based Gas Technology Institute / CRI Catalyst/Shell**	HydroPyrolysis	No data	No data	700,000 t/a	Residential waste, biomass, plastic waste	No data	No data	IH2 Technology; Shell 2019a
9	**Brightmark Energy**	Pyrolysis	in Ashley, Indiana, US	Under construction	100,000 t/a	Plastic waste, mixed plastic residuals from recycling	Diesel, Naphtha. Industrial wax	Diesel and Naphtha to BP	Brightmarkenergy 2019
10	**Quantafuel**	Catalytic pyrolysis and purification	Skive, Dänemark	Planned for fourth quarter 2019	18,000 t/a	No detailed information (plastic from local suppliers, almost all kinds of plastic waste)	Pyrolysis oil purified, ash	BASF (EUR 20 million investment in Quantafuel)	Stark 2019; Quantafuel 2019; William and Burridge 2019
11	**Plastic Energy**	Pyrolysis; patented process Thermal Anaeronbic Conversion (TAC)	2 industrial plants: Sevilla and Almeria, Spain	Since 2014 and 2017	No data (kommerzialisiert)	nicht recycelbare End of Life Plastics (ELP) aus Haushaltsabfällen	Pyrolysis oil (product name TACOIL)	Spanish oil concern Repsol	Plastic Energy 2019a; Plastic Energy 2019b; Messenger 2018
			10 plants planned in Asia and Europe (including 1 with SABIC in the Netherlands; with Petronas in Malaysia)	In the coming years 2020-2023	200,000 t/a from 2020	Non-recyclable End of Life Plastics (ELP) from household waste	Pyrolysis oil (product name TACOIL)	SABIC for PE and PP production	Tullo 2019; Lechleitner 2019; William and Burridge 2019
12	**Vadxx**	Pyrolysis	No data	No data	20,000 t/a	Plastic waste	No data	No data	VADXX 2019
13	**Recycling Technologies**	Pyrolysis, RT7000	No data	No data	9,000 t/a	Plastic waste	No data	No data	The RT7000 / Recycling Technologies 2018
14	**Pyrum Innovations AG**	Thermolysi	Germany (Kaiserslautern and Munich) and worldwide	in operation	Pyrum coke, oil, gas (~2,500 t/a; ~3,700 t/a; ~900 t/a)	Used tyres (plastic waste, CFRP, minerals, bitumen, biomass, packaging (Tetra Pak) etc.)	No data	No data	Pyrum 2017
15	**Licella Holdings Ltd**	Catalytic hydrothermal reaction, Cat-HTRTM	No data	No data	No data Commercial plants	Plastic waste (biomass, used oil)	No data	No data	Licella 2019a

No.	Company	Plant			Capacity	Input	Product(s)	Buyer	Reference
		Procedure, Process	Location	Commis-sioning					
16	Klean Industries	Pyrolysis (and gas-ification)	No data	No data	No data Commer-cial plants	Plastic waste	No data	No data	Klean Industries 2019
17	BASF, ChemCyc-ling Projekt	Pyrolysis	Facilities in Germany, Belgium	End of 2018	Prototypes, not market ready yet	Unsorted, mixed, non-purified plastic waste	Pyrolysis oil, additive "Ccycled" in the name	our pilot products with partners from the automotive and (food) packaging industries, electrical	K-Zeitung 2019; BASF 2019; Ecoloop 2018
18	Arcus Greencyc-ling (coope-ration with KIT)	presu-mably pyrolysis, ARCUS 5.0 SERIES	Industriepark Höchst, Frankfurt	No data	Prototyp 2,200 t/a - 7,000 t/a	Plastic waste PE, PP, PS, ABS, PVC, PET etc.	No data	No data	Arcuss, n. d.
19	LyondellBasell (cooperation with KIT)	Catalytic pyrolysis, MoReTec	Ferrara, Italy	under con-struction	No data Pilot plant	Processing of post-consumer plastic waste	Pyrolysis oil	No data	LyondellBasell 2019
20	OMV Konzern, Raffinerie Schwechat	Pyrolysis in solvent, ReOil®	Ausstria	In opera-tion since 2018	800 t/a (Pilot plant)	Polyolefin	No data	Borealis	OMV 2018; Schubert et al. 2019; William and Burridge 2019
21	Fuenix Joint Venture with Plasma Power	No data, Ecogy® process	Weert, Den-mark	Last quarter of 2019	No data Pilot plant	(unclear)	Pyrolysis oil	Chemical concern Dow for polymer production on site in Terneuzen, the Netherlands	Fuenix 2019; Plasma Power, n. d.; Tullo 2019
22	DEMONT	DeFuel	No data	No data	No data	Plastic waste	No data	No data	Demont 2019
23	Cassandra Oil	Catalytic Pyrolysis	No data	No data	No data Commer-cial plants	Tyres, plastic waste excluding PVC	No data	No data	Cassandra Oil 2019
24	GreenMantra	Catalytic Pyrolysis	No data	No data	No data	Polyolefin	No data	No data	Home - GreenMantra 2019
25	Handerek Technologies	Hydro-cracking	No data	No data	No data	Polyolefin, PS	No data	No data	Handerek Technologies
26	Neste with a) Remondis and b) Ravago	thermo-chemical process	No data	Intended plan without schedule	200,000 t/a	No data	Pyrolysis oil	No data, but Düsseldorf chosen as global hub for supplying the chemical and plastics industry with recycled plastic	William and Burridge 2019
27	Carbios	Depoly-merisation using a modified enzyme	Near Lyon, France	under con-struktion	No data Demons-tration plant	Multi-layer plastics containing PET	Terepht-halic acid (PTA) and ethylene	Consortium with Nestlé Waters, PespiCo, L'Oreal and Suntory	Tullo 2019; William and Burridge 2019
28	Loop Industry	Depolyme-risation by Hydrolyse	Spartanburg, South Carolina, US	under con-struktion	No data (commer-cialised)	PET	Monomers: dimethyl-terephtha-late, mono-ethylene glycol	inter alia, L'OCCITANE. Danone, joint venture with polyester manufac-turer Indorama	Tullo 2019; Loopindustries 2019
			3 further plants, location not given	by 2023					
29	DuPont Teijin Films	Depolyme-risation, LuxCR™	No data	No data	No data	PET	No data	No data	Dupont 2019
30	gr3n	Depoly-merisation (micro-waves) DEMETO Techno-logie	No data	2021	No data (industrial plant)	PET	No data	No data	gr3n recycling 2019
31	BP	Depolyme-risation	Naperville, Illinois, US	Intended in-vestment of $25 million, construc-tion plan-ned for late 2020	Pilot plant	PET	No data	No data	William and Burridge 2019
32	EASTMAN	Depolyme-risation (Methan-wolysi)	US	in planning	No data. (commer-cialisation)	Polyester	No data	No data	Eastman 2019

4.2 Key messages from the literature

Some key messages on central aspects, success factors and challenges of pyrolysis processes have been collected from the literature in Chapter 4.1. These are summarised below. Unless otherwise indicated, they are cited from Lechleitner et al. (2019).

A. Sensitivity of processes to impurities

- Depending on the process, different levels of purity are required and varying degrees of contamination may occur.
- Chemical recycling has lower purity requirements than mechanical recycling.
- During gasification, municipal waste can be converted without pretreatment.
- It is also possible to use highly heterogeneous materials and composite materials in solvolytic processes.
- According to Agilyx (2019), their polystyrene pyrolysis process is unaffected by impurities.
- In thermochemical processes, the composition of the feedstocks tends to determine product quality. When using catalysts, potential catalyst poisons must be evaluated and, if necessary, certain fractions must be removed through additional sorting steps.
- The formation of impurities and/or corrosive substances, such as HCl, can also be controlled to a certain extent through process control (cooling rate).

B. Input materials and their suitability

- Packaging waste with a high amount of **polyolefins** (as there are no heteroatoms) is particularly well suited as feedstock in mixed waste fractions. Moreover, this waste accumulates in large quantities and is easy to sort out due to its use as disposable packaging.
- Conversely, plastics containing **heteroatoms** in their polymer structure, such as chlorine, oxygen, nitrogen and sulphur, can be problematic for the process and reduce product quality. Their degradation products can act as catalyst poisons and/or have a corrosive effect that can damage the facility. Impurities can be removed in additional process steps (e. g. dechlorination).
  Examples:
  PVC – Formation of hydrochloric acid (corrosive)
  PET – Formation of terephthalic acid, which also has the potential for plant blockage through precipitation

C. Possible products and quality

- The thermal degradation of
  - PS, PMMA, (PVC) leads to high monomer recovery (Lopez et al. 2017).
  - PET, PUR leads to the formation of coke during decomposition.
  - PE, PP runs through a radical chain degradation mechanism and produces a relatively broad range of products. Depending on the process conditions, a spectrum of shorter or longer chain, branched or unbranched, aromatic or aliphatic hydrocarbon compounds is formed (Stapf et. al 2018; Lopez et al. 2017).
- The biogenic residues (lignocellulose, proteins, lipids) present in mixed household waste containing plastics demonstrate completely different degradation behaviour compared to plastics (Stapf et. al 2018).

- The different components of mixed waste influence each other's degradation and interact strongly (Stapf et al. 2018, Wilk/Hofbauer 2013b).
- Product distribution can be limited by suitable operating conditions (temperature, heating rate, residence time) (Lopez et al. 2017).
- Essentially, the higher the temperature, the lower the molecular weight of the products (light pyrolysis oil, gas).
- The pyrolysis oil can be processed further in conventional oil refineries and converted back into base materials for plastics production without any loss of quality.
- Since the resulting substances are basic chemical building blocks, there are many possibilities for use and further processing throughout the entire petrochemical industry.
- By choosing a catalyst, it is possible to form branched, ring-shaped and aromatic compounds more precisely compared to purely thermal degradation.
- From a purely technical perspective, pyrolysis processes can be conducted so selectively as to generate a liquid-products share of over 95 per cent.
- Connection to the appropriate infrastructure for further processing is a decisive marketing component. This should be taken into account for economic production in the initial planning stage.

D. Environmental assessment

- Pyrolysis processes are an option for closing carbon cycles. Due to the high energy requirement, however, a contribution to future climate neutrality can only be realised in combination with the expansion and availability of renewable energies.
- A life cycle analysis is being carried out for many industry initiatives. For example, the Technical University of Braunschweig is developing a methodology for the iCAREPLAST Project to assess the life cycle environmental impact of secondary chemical raw materials from the recycling of products containing plastics (iCAREPLAST 2019). BASF would also like its approach to undergo an environmental assessment (Factsheet BASF).

E. Process engineering challenges and reactor configurations

- Plastics have a low thermal conductivity and plastic melt is very viscous.
- It is challenging to set product specifications in-situ in the reactor or through post-treatment (Stapf et al. 2018).
- Another difficulty is "control of the soiling and sticking tendency of the intermediate products in the reactor or during condensation" (Stapf et al. 2018).
- A large-scale travelling bed, rotary kiln or fluidised bed reactors can be used (Stapf et al. 2018). Examples for the use of rotary kilns include the Berlin Process for Plastics from Electrical and Electronic Waste and the Hamburg Process for Fluidised Bed Reactors.

F. Barriers to scaling and commercialisation

At the end of the last century, initial attempts were made to commercialise pyrolysis technologies for the raw material recycling of plastics, but they were widely discontinued due to a lack of economic viability. The application logistics, process technology and product-related hurdles formulated by Lechleitner (2019) are summarised in the following list.

- Lack of availability of the required quality
- Variability of the feedstock
- Complex pretreatment and sorting
- Handling plastic melt
- Reduction of heat input through coking and deposits on the heat exchanger surfaces
- Blockages caused by waxes and high molecular weight intermediates
- Blockages caused by calcium chloride and inorganic aggregates
- Costly cleaning due to coking and blockages
- Products of inferior quality due to wide product range and unstable chemical compounds
- Products of inferior quality due to impurities and heteroatoms
- Low yield
- Plant engineering difficulties when increasing scale

The state of technical development of the individual processes considered in the analysis makes it clear that considerable development efforts will be necessary to make significant contributions to the recycling of plastics or other materials with high calorific value.

Clarifying regulatory questions regarding the imputability to recycling rates will be decisive for such development, including in the case of petrochemical processing. Furthermore, we must determine how to ensure the continuous availability of plastic flows at the appropriate quantity and quality. This will include the necessary sorting and pretreatment efforts to achieve the required purity, which must be taken into account (Lechleitner et al. 2019; Factsheet BASF).

5. ECOLOGICAL ASSESSMENT OF CHEMICAL RECYCLING

Using the processes for chemical recycling described in Chapter 4, plastic waste can be broken down into its constituent raw materials and recycled (e. g. chemical feedstocks such as liquid hydrocarbons for use in steam cracking). This helps to prevent fossil-based chemical production and the incineration of plastic at the end of its life cycle. It is therefore anticipated that chemical recycling processes will reduce both demand for fossil-based resources and greenhouse gas emission levels. By substituting chemical recycling for mechanical recycling, additional performance deficits or so-called "down cycling" of the mechanically-produced recyclates could also be prevented. In many cases, the recyclates that arise from down cycling can ultimately only be incinerated after their supplementary use, thus producing additional greenhouse gas emissions.

In view of the expected ecological benefits, chemical recycling appears intuitively sensible, particularly from the perspective of climate-neutrality, which is the focus of the following analysis. However, the advantages and disadvantages of a circular economy for plastics in general and as a result of chemical recycling are the subject of intense and controversial discussion in scientific literature. Geyer et al. (2016), for example, show that there are no intrinsic environmental benefits in a closed-loop recycling system compared to an open-loop system. According to this publication, it cannot be assumed by default that recycling plastic waste in a closed-loop system is automatically more environmentally beneficial than other methods of recycling. In terms of recycling PET, Shen et al. (2010) show, for example, that the mechanical recycling of PET into textile fibre (open-loop recycling system) is more eco-friendly than chemical recycling of the material into chemical feedstocks (closed-loop recycling system), even though the recycled PET fibres have to be incinerated at the end of their life cycle. Furthermore, previous studies (Lazarevic et al. 2010) demonstrated that, depending on the system conditions, incinerating high calorific plastic waste at cement works can lead to a greater reduction in greenhouse gas emissions than most chemical recycling technologies. This reduction is primarily the result of substituting fossil fuels such as coal with plastic waste. Based on literature sources, it is clear that the intuitive ecological benefits of chemical recycling cannot be guaranteed. It is therefore necessary in **each individual case and in the context of the respective system conditions** (energy supply, alternative options, development trends, etc.) to investigate whether ecological benefits can be achieved by means of chemical recycling over an appropriate period of time (dynamically).

To this end, the general methodology for the ecological assessment (life cycle assessment) of recycling options for plastic waste is outlined and applied in this chapter. Alongside chemical recycling, other recycling technologies for plastic waste are also included.

Based on the methodical foundations of the life cycle assessment, indicative evaluations of the processes are then carried out for the plastic waste streams identified in Chapter 6. In this way, initial statements can be made and conclusions drawn regarding the ecological potential of chemical recycling and, more specifically, pyrolysis of plastic waste in terms of their contribution to defossiling the chemical and plastics processing industries in NRW.

5.1 Ecological assessment of plastic waste recycling

5.1.1 General methodology for the ecological assessment of recycling technologies

Originally, plastic waste recycling technologies were used to prevent plastic waste being dumped in landfill and to reduce the volume of waste generated. In NRW, dumping plastic waste in landfill is banned, so plastic waste is mainly incinerated to recover its energy content. Introducing a new recycling technology, therefore, will not replace dumping plastic waste in landfill, but will substitute another recycling technology that is already in use (e. g. incineration to recover energy content) (see Figure 6).

In contrast to dumping waste in landfill, in most cases the recycling technologies that are currently in use already produce a valuable product, which also originally replaced a primary product (here primary product 1). If the recycling technology currently in use is substituted, the original product will also have to be provided by different means.

If a new recycling technology produces another valuable product (here primary product 2), the production of an equivalent primary product and the environmental impact associated with its production will be avoided by the introduction of this technology.

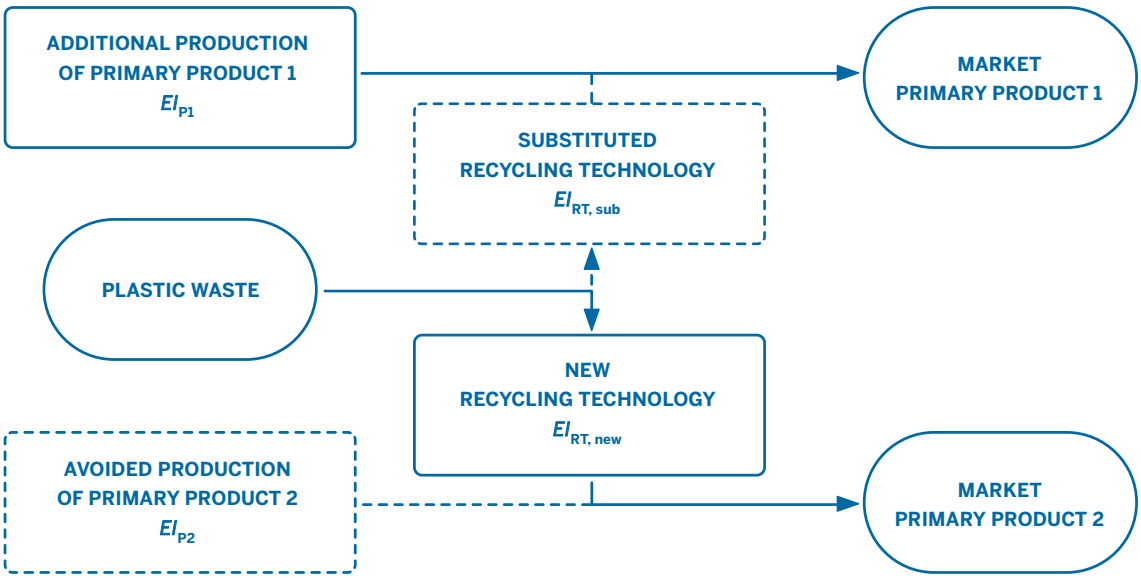

Figure 6: Impact of the introduction of a new form of recycling technology.

In reality, it may be the case that these substitution effects do not occur on a one-to-one basis because other displacement effects arise, for example due to market responses. However, these complex market-driven substitution effects are not taken into account in the analysis presented here.

In order to evaluate the environmental impact of introducing a new recycling technology, four facts need to be taken into consideration: the new recycling technology prevents (1) the environmental impact of primary product 2 (EI_{P2}) and (2) the substituted recycling technology ($EI_{RT, sub}$). However, its introduction also leads to an increase in the environmental impact of the overall system due to (3) the new recycling

technology itself ($EI_{RT,\,new}$) and (4) the additional production of primary product 1 of the avoided recycling technology (EI_{P1}). A new recycling technology only reduces environmental impacts in the following case:

$$\overbrace{(EI_{P2}+EI_{RT,\,sub})}^{\text{Reduction}} - \overbrace{(EI_{RT,\,new}+EI_{P1})}^{\text{Increase}} > 0$$

In other words, because of its complex repercussions, the introduction of a new recycling technology does not necessarily lead to a reduction in environmental impacts. On the other hand, it is also true, in view of these complex repercussions, that existing systems cannot be considered intrinsically more beneficial in ecological terms.

Recycling technologies for plastic waste should therefore be examined as part of a systematic life cycle assessment without any preconceived views on the outcomes, so that the technologies that reduce environmental impacts, particularly greenhouse gas emissions, are identified.

5.1.2 Aim and scope of the ecological assessment

The aim of this ecological assessment is to formulate forward-looking statements that estimate the potential to reduce greenhouse gas emissions by introducing pyrolysis in NRW. The focus is on plastic waste that is currently disposed of at waste incineration plants (see Chapter 6). This plastic waste is likely to be irrelevant for mechanical recycling in the near future and also leads to problems for waste incineration plants due to its extremely high calorific value. Waste incineration plants can therefore be defined as a reference value in the initial stage and as the recycling technology to be replaced. Since the pyrolysis process cannot be operated using ordinary household waste, however, it is assumed that sorted and mixed plastic waste will be disposed of using the respective recycling technologies.

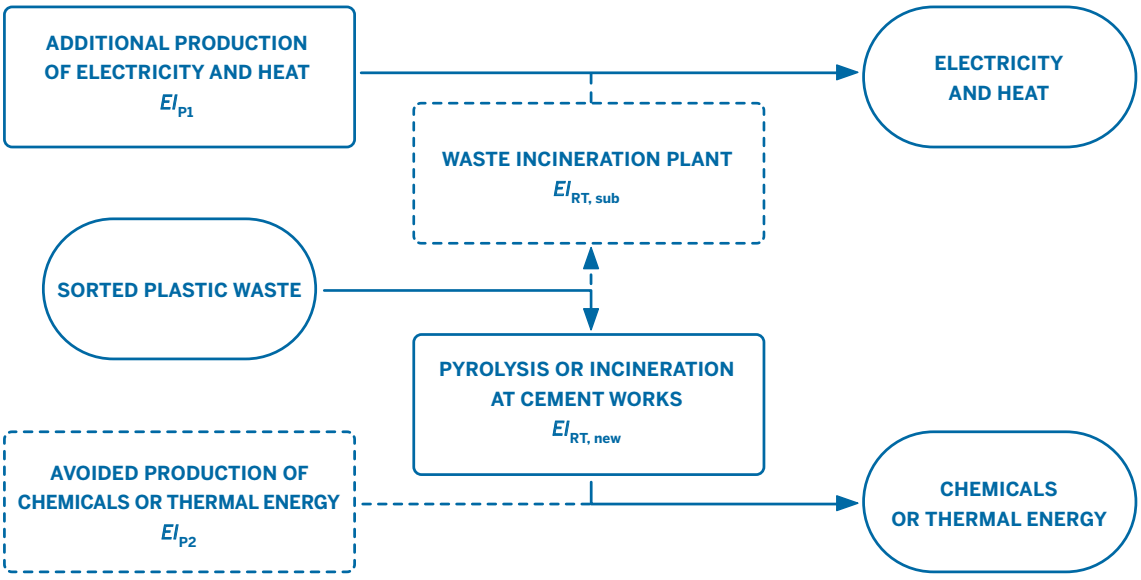

Figure 7: Aim and scope of the ecological assessment.

For this analysis of potential, the scope is defined as a comparison between waste incineration and pyrolysis. This means it is possible to answer the question regarding the potential of pyrolysis to reduce greenhouse gas emissions compared to the current recycling technology, namely waste incineration. In addition to this, the scope is expanded to include other recycling technologies as alternatives to pyrolysis. This also allows us to answer the question as to which recycling option generally offers the greatest ecological reduction potential for the plastic waste under analysis.

Mechanical recycling processes are currently excluded for the plastic waste to be analyzed, which is currently disposed of at waste incineration plants, as the waste is too contaminated. In addition to being used at waste incineration plants, plastic waste is also used at cement works as a secondary raw material (so-called refuse derived fuel – RDF). As the envisaged waste stream is normally co-incinerated at cement works, the scope is therefore also broadened to include this.

In addition to the recycling technologies that are substituted, policy conditions play an important role in the ecological assessment. The energy system and the supply of electricity, in particular, will change significantly in the future. This change will have a particular impact on the greenhouse gas emissions avoided through electricity or thermal energy products at waste incineration plants or co-incineration at cement works. The ecological assessment has therefore also been broadened to include a Scenario for energy supply in 2050, in which energy supply is largely based on renewable energy sources (wind and biomass) in both cases.

5.1.3 Functional unit

The functional unit in a life cycle assessment quantifies the function of the system being investigated and serves as a basis for comparing product systems. In this specific case, the functional unit is defined as the treatment of one kilogram of plastic waste.

Previous life cycle assessment studies (Lazarevic et al. 2010) have shown that the composition of plastic waste has a strong influence on the conclusions reached. The composition of the plastic waste must therefore be included in the functional unit so as to ensure that all recycling technologies use the same kind of plastic waste and are thus comparable.

Pyrolysis procedures are not currently technically suitable for processing household waste or lightweight packaging waste without it being sorted beforehand, so it is assumed in the analysis that the waste is sorted. There are approximately 90 specialised sorting plants in Germany for producing sorted plastic waste (ITAD 2015), and these currently sort the plastic waste collected in yellow bags or as household waste. A sensor-based automatic sorting system is used for classifying plastics. The most important method is nearinfrared spectrometry, which recognises different types of plastic (Christiani 2017). Plastic fractions that can be clearly categorised and sorted, e. g. PE film, are usually recycled mechanically, while plastic waste that cannot be clearly categorised ends up in the mixed plastic waste fraction (MPW). This MPW fraction is currently recycled thermally for the most part and is therefore accepted as input for the present study.

The composition of the MPW fraction can be estimated, for example, by the green dot specifications, according to which the MPW fraction has a maximum contaminant content of ten per cent, consisting mainly of paper, cardboard, metallic and other contaminants (Duales System Deutschland 2019). The polymer content in the MPW fraction can be estimated approximately using the constitution of the production volumes for packaging (Conversio 2018). Table 3 summarises the composition of the MPW fraction.

Table 3: Composition of the mixed plastic fraction for the present analysis (Conversio 2018).

Component	**PE (LD/HD)**	**PET**	**PS**	**PP**	**PVC**	**Residual materials**
Percentage	48 %	16 %	3 %	19 %	4 %	10 %

System boundaries and inventory

The system boundaries of the individual recycling technologies are shown in Figure 8.

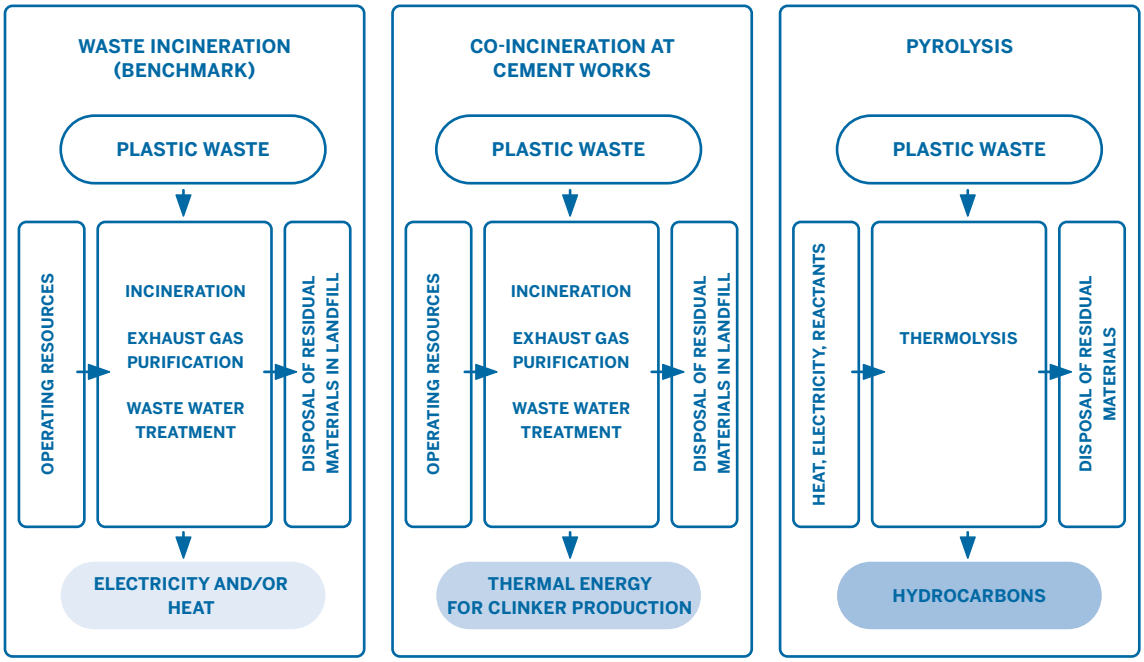

Figure 8: System boundaries for assessing the reduction potential of pyrolysis/thermolysis.

Definitions and assumptions for waste incineration and co-incineration at cement works

A model taken from commercial life cycle inventories is used for the utilisation of plastic waste at waste incineration plants (Doka 2013), which shows the current state of the art for waste incineration plants. The system boundaries for waste incineration plants include the incineration itself, exhaust gas purification and waste water treatment. In addition, all the environmental impacts of providing the operating resources (e. g. caustic soda) and the disposal of residual materials to landfill are included.

To calculate all the elementary flows of waste incineration, the model needs the elemental composition of the plastic waste as input. The elementary flows into the air, soil and water are calculated based on the transfer coefficient for each material element (e. g. elemental carbon C). For each element, the need for operating resources such as detergent or natural gas and the residual materials are also calculated based on measured data from Swiss waste incineration plants. The greenhouse gas emissions from providing the operating resources and disposing of the residual materials are taken from commercial life cycle inventories (Swiss Centre for Life Cycle Inventories 2017 und thinkstep AG 2017).

On average, waste incineration plants have an efficiency level of 41 per cent and a power coefficient of 0.35 (Eriksson et al. 2009). The reduction in greenhouse gas emissions through the pro-vision of electricity is based on the current electricity mix in Germany and an assumption of the future electricity mix in 2050 (thinkstep AG 2017). In the case of heat production, it is assumed that the greenhouse gas emissions from district heating are substituted. Current district heating was modelled on the basis of burning 44 per cent natural gas and 56 per cent energy from other sources e. g. biomass, oil and brown coal (Connolly et al. 2014). For 2050, the provision of district heating is modelled exclusively on the basis of biogenic resources. All the data sets for avoided greenhouse gas emissions come from LCA databases with the exception of biomass for heat production, which was taken from Gerssen-Gondelach et al. (2014).

For co-incineration at cement works, it is assumed that the exhaust gas purification systems are identical to those at waste incineration plants. This can be justified as an initial assumption since both waste incineration plants and cement works burn plastic waste that is subject to the German Federal Emission Control Ordinance (BImSchV) and therefore have to comply with the same maximum emission levels. However, this was not yet the case in 2015 at least, since at this time most cement works did not comply with the Emission Control Ordinance as they were exempt. Since then, SCR systems to reduce NOx emissions have been installed at other cement works in Germany.[3] The extent to which all cement works have now been upgraded requires further review (Schönberger & Waltisberg 2014 and Orosz 2018). Regarding the calculation of greenhouse gas emissions for co-incineration at cement works, the present study assumes an optimistic stance and uses the same model as for waste incineration plants.

In the case of co-incineration at cement works, it is assumed that brown coal is substituted at the energy level (calorific value) of the plastic waste under analysis. The environmental impact of the supply of brown coal is provided by life cycle inventories (Swiss Centre for Life Cycle Inventories 2017). The avoided environmental impacts of burning brown coal at cement works are calculated in a similar way to those in the model already presented, based on the elementary composition of the fuel (or waste).

In order to identify the fuel that is avoided in the case of co-incineration at cement works in the future, an assumption needs to be made regarding the future composition of the fuel at cement works. The International Energy Agency (IEA 2018) forecasts that the amount of brown coal used as fuel in the cement industry in Europe will have decreased to about 20 - 22 per cent by 2030. Accordingly, a further reduction in the proportion of coal in the fuel mix can be assumed by 2050. In order to portray the impact of substituting this fuel with plastic waste at cement works, three scenarios are considered for 2050: substitution of brown coal with natural gas, heating oil and biomass, e. g. pellets made from waste wood.

Definitions and assumptions regarding pyrolysis

The system boundaries for pyrolysis include the pyrolysis process itself and the provision of all the energy required for implementation (electricity and heat) and other auxiliary materials. In addition, any potential residual materials that arise need to be disposed of.

Due to the stage of development, data on pyrolysis are not yet recorded as standard in the relevant life cycle inventories. They have to be modelled on the scientific literature for the purpose of investigation. Data taken from Perugini et al. (2005) are used for this life cycle assessment (see Table 4). The two pyrolysis technologies outlined by Perugini et al. (2005) are based on the procedures used by Veba Oel AG and BP.

The process data used by Perugini et al. (2005) were compiled a long time ago, so modern-day plants or process variants may present different values as a result of increased energy efficiency. Since the two processes involve very different energy needs, however, the data sets allow us to gain an impression of the range of pyrolysis systems and the resulting potential to reduce greenhouse gas emissions. In future projects, the data for pyrolysis will have to be updated.

In BP's plant design, the collected and sorted mixed plastic is first shredded and contaminants are removed. The processed mixed plastic is then pyrolysed in a fluidised bed reactor, whereby the waste is melted and broken down in a layer of sand by means of thermal cracking. The gaseous hydrocarbons then leave the reactor in the fluidised bed and are purified in a cyclone system. The gas emitted is then partially condensed into a liquid hydrocarbon product in a two-stage process. The liquid hydrocarbons can be directly processed into petrochemical products in a steam cracker unit. Gaseous hydrocarbons can be used as energy to heat the pyrolysis process.

[3] The SCR technology for NOx reduction additionally requires around five kWh/t of clinker however (from 2010 to 2014 the demand for electrical power amounted to around 110 kWh/t cement) (Schönberger & Waltisberg 2014).

Table 4: Extract of the process data for pyrolysis technologies from Perugini et al. (2005).

	Flow	**Unit**	**Pyrolysis (BP)**	**Pyrolysis (Veba)**
Plastic waste	Mixed plastics	in kg	1.00	1.00
Inputs	Thermal energy	in MJ	0.131	4.732
	Electricity	in kWh	0.059	0.960
	Hydrogen	in kg	0.002	0.011
Outputs	Liquid hydrocarbons	in kg	0.713	0.822
	Gaseous hydrocarbons	in kg	0.147	0.090

The process developed by Veba Oel AG involves a pyrolysis procedure for processing MPW and dates back to a publication by Dijkema und Stougie (1994). After the depolymerisation of the MPW, there is a processing stage that consists of an alkaline washing process and a hydrogen treatment, which produces a synthetic mineral oil substitute. According to Perugini et al. (2005), this synthetic mineral oil substitute can be processed at any refinery. During the washing process and the hydrogen treatment, gaseous hydrocarbons also accrue, which can be used as a source of energy.

In terms of the liquid hydrocarbons produced, it is assumed that they substitute naphtha on a one-to-one mass basis. As regards the gaseous hydrocarbons, LPG is assumed to be the substituted product. The greenhouse gas emissions for all energy, auxiliary materials and the avoided production of naphtha are taken from commercial life cycle inventories (Swiss Centre for Life Cycle Inventories 2017 and thinkstep AG 2017). For both processes, it is also assumed that all residual materials are disposed of at waste incineration plants.

5.2 Indicative process assessment and conclusions

5.2.1 General overview of the results, key points and conclusions

An initial indicative process assessment was conducted based on Section 5.1. An overview of the results is given and provisional conclusions are drawn regarding the potential that the various recycling technologies have to reduce the level of ecological impact (See Figure 9).

The results are given regarding the aim and scope defined in Section 5.1.2 and for greenhouse gas emissions in kilograms of CO_2-equivalents. Positive values indicate that the alternative recycling technology can reduce greenhouse gas emissions in comparison to waste incineration plants. Negative values (blue) indicate that the alternative recycling technology does not show any benefits and, in this case, the plastic waste should continue to be recycled at waste incineration plants. Fields with a grey background indicate that the comparison was not carried out for that specific year.

	Pyrolysis (BP)	Pyrolysis (Veba)	Cement works MPW instead of coal	Cement works MPW instead of oil	Cement works MPW instead of natural gas	Cement works MPW instead of biomass
2020	1.44	0.55	1.96	–	–	–
2050	2.48	1.78	–	2.26	1.35	-0.10

Figure 9: Potential to reduce greenhouse gas emissions in kilograms of CO_2-equivalents in comparison to waste incineration plants (MPW = mixed plastic waste).

Conclusions drawn from the results:

1. In terms of the pyrolysis recycling technology, the waste volumes that are currently incinerated at waste incineration plants should initially be used. In this area, pyrolysis already shows a robust potential to reduce greenhouse gas emissions by between 0.55 and 1.44 kilograms of CO_2-equivalents per kilogram of waste used.

2. The results for pyrolysis also illustrate that energy efficiency has a great impact on the potential to reduce greenhouse gas emissions. The reduction potential of the Veba process is currently 62 per cent lower than the BP process. This difference is based primarily on the thermal energy requirement of the Veba process, which is 36 times higher than that of the BP process. This difference is primarily attributed to the fact that, in the BP process, the condensed gaseous hydrocarbons that are produced as a by-product are not used as fuel to heat the reactor. In future studies, particular attention should there-fore be paid to the energy efficiency of pyrolysis in the synthesis of the process.

3. The reduction potential using the pyrolysis recycling technology will improve in the future due to the lower greenhouse gas emissions from the energy system. This improvement can be explained by the greater proportion of renewable energy used to generate electricity and district heating, which will result in a lower emission credit entry for waste incineration.

4. Under the current conditions, waste with a high calorific value consisting of mixed plastic waste with a high percentage of polyolefins, such as in the present study, should be incinerated at cement works as long as coal can be substituted with mixed plastic waste. The potential of this use to reduce greenhouse gas emissions compared to pyrolysis at cement works and the substitution of coal is 27 per cent (BP process) and 72 per cent (Veba process) higher respectively.

5. In future, it will be necessary to ensure that cement works do not use plastic waste as a substitute for the alternative fuels oil, natural gas or biomass, which generate lower greenhouse gas emissions. The results compared to other fuels illustrate that mixed plastic waste should not be used as a substitute for biomass (-0.1 kilograms of CO_2-equivalents). In contrast to biomass, mixed plastic waste should, however, be incinerated at cement works instead of at waste incineration plants, if oil (reduction of 2.26 kilograms of CO_2-equivalents by 2050) or natural gas (reduction of 1.35 kilograms of CO_2-equivalents by 2050) is substituted as fuel. However, energy-efficient pyrolysis processes seem ecologically beneficial compared to utilisation at cement works, since pyrolysis demonstrates a higher reduction in greenhouse gas emissions.

5.2.2 Open questions and further research required

The evaluation of the possible ecological impact and particularly of the potential to reduce greenhouse gas emissions in this discussion paper provides a preliminary statement of direction. Further analytical steps are required for a more extensive assessment and should include the following points:

1. In order to carry out an ISO-compliant ecological assessment of chemical recycling compared to alternative recycling technologies, an additional independent "critical review" is necessary. This critical review can be carried out in the course of a follow-up project.

2. The outdated database for pyrolysis technologies must be updated in order to make the results of the life cycle assessment more robust in the face of uncertainties in the under-lying data.

3. The analysis of potential plastic waste as raw material for pyrolysis should be broadened to include further potential material flows. This would allow a comprehensive picture of the potential pyrolysis offers to reduce greenhouse gas emissions to be formed. This could also include mixed plastic waste and groups of substances beyond the packaging collected in yellow sacks, e. g. polycarbonates, polyurethane and/or nylon.

4. The analysis should also be broadened to include a model for the chemical industry. This model should likewise reflect the production of the substituted chemicals depending on the changing conditions in the chemical industry. In the chemical industry of the future, measures (such as hydrogen from electrolysis using renewable power or the use of CO_2 as a raw material) will also come into effect, thereby significantly changing the environ-mental impact of chemical products. In this context, the environmental impact of the chemical products substituted by pyrolysis will also change.

5. The results of co-incineration at cement works also show that only a system-wide model-ling approach including all raw material industries (chemicals, refineries, steel, cement, energy, etc.) can portray the reduction in greenhouse gas emissions as a result of pyrolysis. This system-wide modelling approach would make it possible to illustrate all the interdependencies and trade-offs (from the fuel that is substituted at the cement works right up to future chemical production) and thus to assess the reduction in greenhouse gas emissions in a holistic way.

6. ESTIMATE OF MASS FLOWS IN NRW

6.1 Estimated volume of plastic waste and how it is recycled in NRW (potential input for chemical recycling)

The quantities of waste recorded by the NRW State Statistical Office at waste treatment plants form the basis for modelling work regarding plastic waste. The structure of waste statistics is divided up into categories using waste code numbers depending on the type of waste, in compliance with the German Waste Catalogue Regulation (AVV) and according to the inputs and outputs or the various waste treatment plants. Upon request, the NRW State Statistical Office made the waste statistics for North Rhine-Westphalia available using a highly detailed six-digit waste nomenclature. This makes it possible to classify the volumes of waste in NRW in a very detailed way according to their origin at the respective treatment plants. (See Fig. 10, Fig. 11 and Fig. 12).

The recovery and treatment methods in the waste statistics generally divide the outgoing waste into the categories of "disposal", "recovery" and "other uses". While the waste for "recovery" is recycled or used to generate energy at other plants, the waste for "disposal" is permanently removed from the circular economy. The waste in the "other uses" category consists of items that are already secondary resources supplied directly to recyclers or to other sectors. The problem with the category of "recovery", therefore, is that certain volumes of waste may be counted several times as input and output at different waste treatment plants.

In addition, the distinction between waste collected in NRW and waste collected in other German federal states is interesting for waste statistics in the state of NRW as it allows us to calculate what proportion of the waste treated here is actually generated in NRW. Furthermore, the waste imported from other federal states can also be determined according to the corresponding highly detailed waste code. The Sankey diagram (Fig. 11) shows the foreign imports of (plastic) waste, although the figures are only given in total.

Calculating the proportion of plastic in the waste streams

The proportion of plastic in the waste categories under investigation was determined using the values of the ABANDA waste analysis database of the state of NRW and external literature from various scientific projects and sorting trials. The information on the plastic content according to waste code number was taken from the final report of the Federal Environmental Agency (UBA) project "Stoffstromorientierte Ermittlung des Beitrags der Sekundärrohstoffwirtschaft zur Schonung von Primärrohstoffen und Steigerung der Ressourcenproduktivität – ReSek" (Flow-orientated identification of the contribution of the secondary raw materials sector towards conserving primary raw materials and increasing resource productivity – ReSek) (Steger et al. 2018) and are expanded in Appendix 9.4.

The analysis of the flow of materials using waste statistics only makes it possible to record residual materials that have been categorised as waste. This is generally post-consumer waste. Production residues that are either channelled back immediately for further processing or bought up directly by processors and/or compounders on account of their high degree of purity are not included in the volume framework of waste statistics and also have to be estimated. The assumption that the proportion of post-production waste from plastic production and processing that is recycled without being categorised as waste is more or less equivalent to the amount found in waste statistics was taken from ReSek (Steger et al. 2018). The proportion of internal recycling during processing was taken on a percentage basis from the data given in "Stoffstrombild Kunststoffe in Deutschland 2017" (Material flow for plastics in Germany in 2017) (Conversio 2018) and applied to the volumes in NRW.

Furthermore, there is a functioning closed-loop circulation for individual deposit systems for plastic goods. In the first instance this involves collection systems for reusable bottles made of PET, along with initiatives such as REWINDO for used PVC windows or collection systems for used agricultural plastic sheeting.

While the volume of plastic in deposit systems for PET bottles was estimated on a percentage basis from an earlier Conversio study (previously under the name of Consultic), it is still not clear in the case of systems such as REWINDO whether the quantities have already been included elsewhere.

Based on calculations from these different evaluation stages (waste statistics for the state of NRW and the proportion of plastics under the various waste code numbers, and the estimate of different post-production residual materials), the volume of plastic waste available for recycling or disposal for the state of NRW in 2017 amounted to 2.4 million tonnes (Fig. 10). This figure does not include the volume of plastic waste from deposit systems for PET bottles (0.12 million tonnes) or internal recycling (0.08 million tonnes), since this material is recycled directly for raw materials on account of its high degree of purity.

Type of treatment

No independent studies, data or information are available for NRW that would allow us to establish specifically the various recovery methods and use of recyclates in different sectors. At the same time, NRW, being a densely-populated state covering a large territory with both rural regions and highly populated urban centres, is a reflection of the Federal Republic of Germany, so it seems plausible to assume that taking a percentage proportion of the information for Germany as a whole, as found in the Conversio study (2018) and Steger et al. (2018), would provide a fairly accurate estimate of the plastic material flows for NRW.

The data from the study "Stoffstrombild Kunststoffe in Deutschland 2017" (Material flow for plastics in Germany in 2017) (Conversio 2018) are therefore decisive for calculating the volume framework in NRW, since these data provide the percentage distribution used for the volume of plastic waste recycled for raw materials in NRW, particularly with regard to material recovery and the follow-up stages (such as producing recyclates, losses, exports, recyclate use in different sectors).

In terms of post-consumer waste and imports, the proportions of the different plastic waste fractions disposed of, recycled or used to generate energy were also taken from the situation for Germany as a whole described in the Conversio study. However, the sources related to plastic waste in the Conversio study (2018, p. 81) are not completely identical to the waste code numbers related to plastic from the waste statistics. Some of the sources therefore had to be grouped together into AVV groups with appropriate weighting.

As is evident in the Sankey diagram, plastic waste is, to a large extent, used to generate energy. For example, the residual waste from households or household-type commercial waste is almost entirely used to generate energy. Even 60 per cent of commercial packaging is incinerated, not recycled as raw materials. This energy recovery takes place either directly as co-incineration at waste incineration plants (WIPs) or as pre-treated substitute fuels (SFs) that are either used to generate energy in SF power plants or as SF in the cement industry, for example. To calculate the volume of plastic waste that is used to generate energy at WIPs or as SF, a proportion of 40/60 (SF/WIP) was taken from ReSek (Steger et al. 2018). This proportion is only slightly different from the Conversio study.

Of the 2.4 million tonnes of plastic waste accrued in NRW in 2017, it is estimated that one million tonnes was used directly to generate energy at WIPs and that 1.4 tonnes underwent some sort of pre-treatment such as shredding, cleaning and sorting (and possibly other processing stages). Disposal in landfill was negligible at 20,000 tonnes. Of the 1.4 million tonnes, only 0.5 million tonnes were really consigned to material recycling. The rest (nearly 0.9 million tonnes) was also used to generate energy, mainly as substitute fuel (0.68 million tonnes) due to its greater homogeneity compared to mixed waste.

Alongside plastic waste from internal recycling in the plastic processing and production sector and the predominantly PET waste from the drinks bottle deposit system, around 0.7 million tonnes of plastic waste was available in NRW for material recovery. A very small proportion (around 10,000 tonnes) of these 0.7 million tonnes was consigned to feedstock recycling, i. e. chemical recycling. The overwhelming majority of this (0.69 million tonnes) was recovered as raw materials.

The distribution between domestic recyclate production and exports for material recovery was taken on a proportional basis from the "Stoffstrombild Kunststoffe Deutschland" (Material flow for plastics in Germany) (Conversio 2018). Since internal imports and exports between individual states within Germany are not relevant, it is unclear whether imports and exports at federal state level that illustrate links between German domestic suppliers and international trade relations may perhaps have been higher. The domestic flows of goods within Germany are, however, very difficult to ascertain. Therefore, in the absence of better data, the import and export pro-portions for Germany were also used for the state of NRW.

Of the 0.69 million tonnes of plastic waste that were available for material recovery in NRW, we estimate that 0.55 million tonnes of plastic waste were used to produce recyclates in NRW after taking imports and exports into account. The processing losses of 90,000 tonnes that occurred in the course of this pro-duction were also used to generate energy, so in end effect 0.46 million tonnes of plastic recyclates were available for the manufacture of new plastic products. Together with the 30,000 tonnes of recyclates used by recyclers from their own plastic waste, this means that just under 0.5 million tonnes of recyclates were used in the plastics processing industry in NRW.

Almost 37 per cent of the recyclates were used for products in the building industry, mainly windows and road construction products such as barriers or bollards, as well as sewage and drainage pipes. Agricultural products, such as flower pots and rainwater barrels, is another relevant field of use for recycled plastic. In addition, a significant volume of recycled plastic is used in the area of packaging, particularly drinks bottles or plastic film for shipping and pallets. With the exception of drinks bottles, which are largely kept in a closed loop, in most areas where recycled plastic is used it is still common that colour purity or sensory quality attributes play an insignificant role or are no issue at all, since more importance is placed on the purely material properties.

6.2 Perspectives for chemical recycling

As outlined above, chemical recycling has played a minimal role to date in recycling plastic waste in NRW (and throughout Germany as a whole). A mere 10,000 tonnes of the approximate total of 2.4 million tonnes of plastic waste in NRW were recycled as feedstock. At the same time, the volume of plastic waste used to generate energy (amounting to 1.9 million tonnes) is extremely high (Fig. 11).

Simultaneously, the low recycling rate for plastics is currently the subject of intense debate. Statutory regulations such as the packaging law are intended to substantially increase the rate of recycling for pack-aging and thereby expand the proportion available for (material) recycling. Above all, this is to be achieved by means of better sorting and would thus primarily be at the expense of the material flow that has served as a substitute fuel until now.

The highly-contaminated and heterogeneous waste that is currently used to generate energy at WIPs is in all probability unlikely to be suitable for (material) recycling even in the future. At the same time, many WIP operators have problems with the large proportion of high calorific plastic waste in the co-combustion fraction at WIPs and have to pre-treat this high calorific fraction by mixing it with low calorific waste or dampening it in order to co-incinerate it at the WPI. Therefore, chemical recycling of these quantitively relevant but highly contaminated and heterogeneous waste fractions would probably be welcome from a waste management perspective, since it would appear to be possible to achieve this without any canni-balisation effects. The objective would be to increase the proportion of material recycling from waste that is currently still being used as substitute fuel.

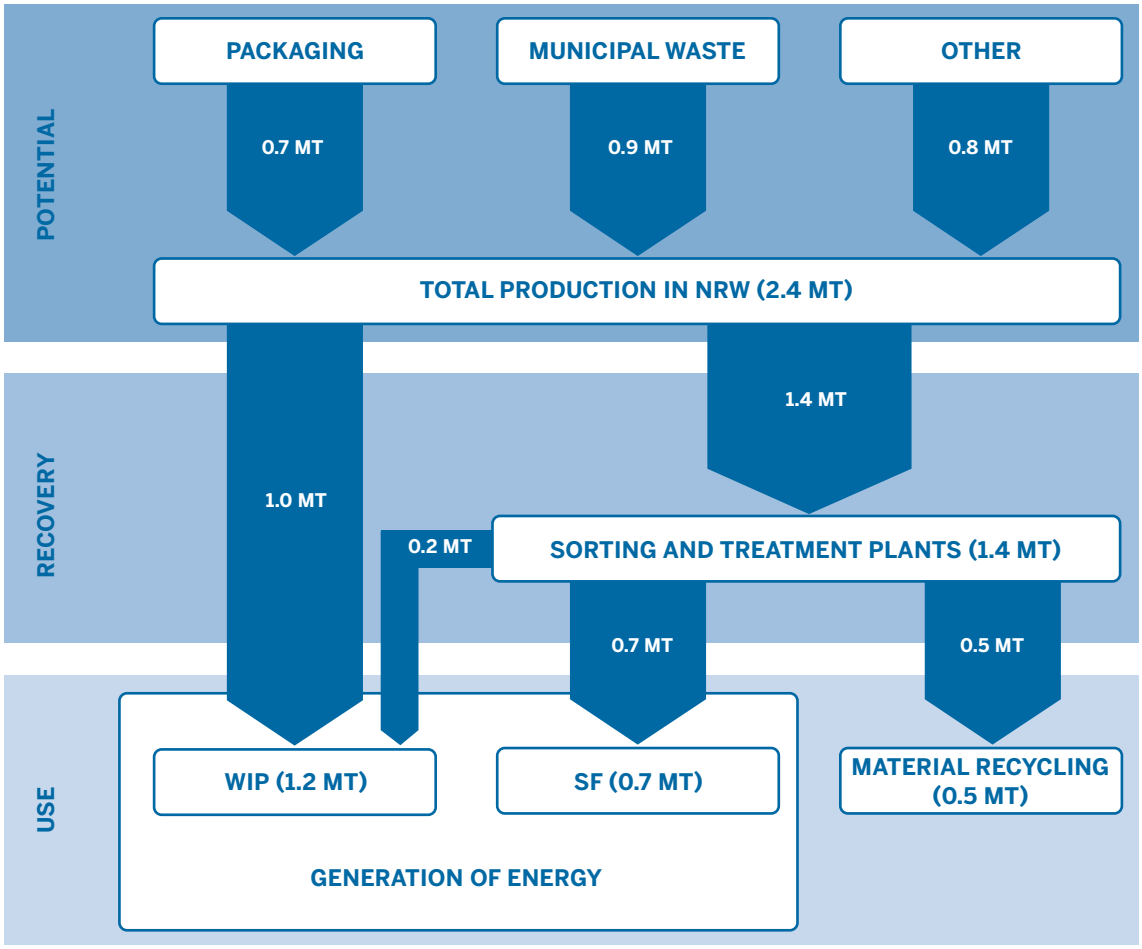

Figure 10: Simplified representation of the material flows of plastic waste in NRW (2017, internal calculation by the Wuppertal Institute).

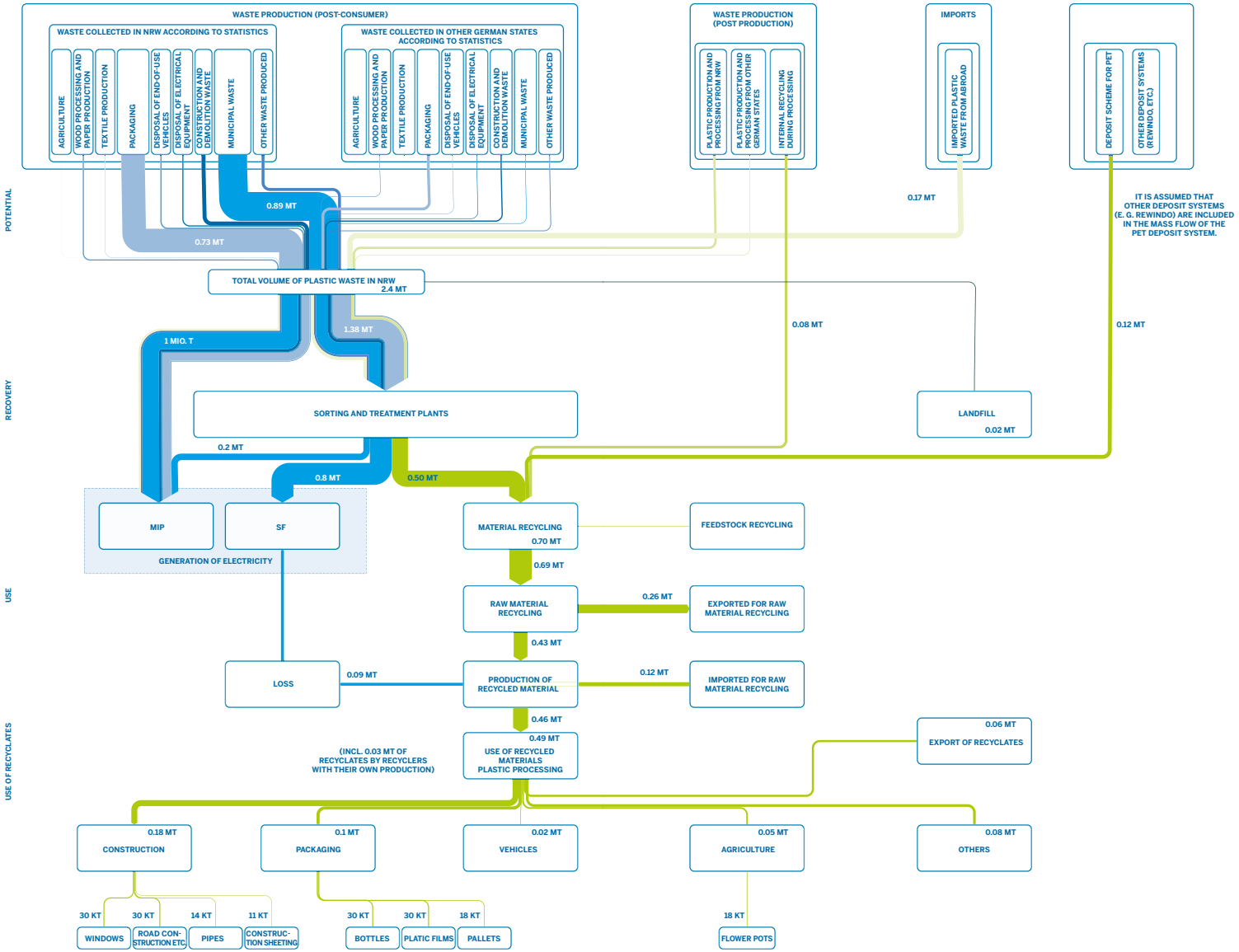

Figure 11: Representation of the material flows of plastic waste in NRW (2017, internal calculation by the Wuppertal Institute).

Figure 12: Overview of the volume framework and material flows in plastic waste in NRW (2017, internal calculation by the Wuppertal Institute).

All figures in tonnes

Statistically recorded waste (proportion of plastic)	From NRW	From other German states	From abroad	Total		Volume recycled (domestic sources)	Volume used for energy (domestic sources)	Volume sent to landfill (domestic sources)		Volume sent to WIPs (thermal processing)	Input for sorting and treatment plants	Input for preparation for material recycling	Volume used for SF
Agriculture	666	12	0	678		274	394	10		236	432	274	158
Wood processing & paper production	35.358	14.181	2.663	52.202		13.082	36.006	451		21.604	27.484	13.082	14.402
Textiles	18.563	371	392	19.326		5.000	13.762	172		8.257	10.505	5.000	5.505
Other production	89.959	21.430	3.802	115.191		29.415	80.960	1.014		48.576	61.799	29.415	32.384
Packaging	727.689	86.087	86.283	900.059		407.284	405.699	792		243.420	569.564	407.284	162.280
End-of-use vehicles	40.385	9.754	14.346	64.485		12.334	36.465	1.341		21.879	26.920	12.334	14.586
Electrical equipment	36.134	16.109	13.075	65.318		10.999	41.244	0		24.747	27.496	10.999	16.498
Construction and demolition	123.137	36.474	11.518	171.129		45.465	110.599	3.547		66.359	89.705	45.465	44.240
Municipal waste	890.816	13.660	28.261	932.737		30.066	862.509	11.901		517.506	375.069	30.066	345.004
Plastics production / processing via waste statistics	69.114	14.756	5.999	89.869		83.870	0	0		0	83.870	83.870	0
			166.339	**2.410.994**	**Im-ports**	**61.495**	**103.686**	**1.158**	**166.339**	**62.212**	**102.970**	**61.495**	**41.474**
					Total	**699.283**	**1.691.325**	**20.386**	**2.410.994**	**1.014.795**	**1.375.813**	**699.283**	**676.530**

Table below taken from Conversio 2018

Total material recycling	**704.788**
Volume used for recycling raw materials	12.236
Volume used for material recycling	**692.552**
Volume exported	266.558
Volume recycled in NRW	425.994
Production of recyclates in NRW	**425.994**
Volume of loss (used as SF)	89.683
Additional im-ported recyclates	124.560
Use of recyclates in NRW (incl. 33k of own recyclates)	**493.879**
Volume of exports	64.771
Used in cons-truction	184.285
Used in packaging	97.005
Used in vehicles	18.720
Used in agriculture	48.138
Other uses	80.959

Total material recycling

Input preparation material recycling	**699.283**
Volume of combustible segregated waste for WIPs	**199.995**
Material recycling	**499.288**
Additional PET deposit schemes	120.000
Additional plastic processing from internal recycling	85.500
Total material recycling	**704.788**

7. SUMMARY AND CONCLUSIONS REGARDING FURTHER RESEARCH REQUIRED

7.1 Summary

This study by the Circular Economy Working Group discussed and compiled the essential foundations for the assessment and design of procedure routes for the chemical recycling of mixed plastic waste. The main results of the study are as follows

The technical basis for plastic pyrolysis already exists

The overview of current research and development activities on recycling plastic waste by means of thermochemical treatment shows a wide basis of works on gasification and pyrolysis. Industrial pyrolysis initiatives that already have commercial ambitions to some extent would appear to be increasing in number. It can therefore be assumed that plastic pyrolysis is feasible in terms of the necessary technical basis.

Further R&D is required specifically regarding the chemical recycling of plastic waste

The working hypothesis was confirmed. The strategically relevant option of recycling mixed and contaminated waste by means of pyrolysis is not yet commercially available. There is a need for further development, particularly at the stage of industrial development and demonstration (TRL 5-9).

Feedstocks for chemical recycling are available in NRW

Significant volumes of mixed plastic waste are currently not yet being recycled for material or feedstock in NRW. From the estimated current volume flows of up to two million tonnes per year, it can be expected that commercial facilities of a typical size will be used to capacity even if the overall volume and structure of plastic waste changes in the future. An expansion of the catchment area to include neighbouring German states or the Benelux countries would further guarantee the feedstock base.

Chemical recycling would appear to be potentially useful in terms of climate policy

The methods for ecological assessment are available and can furnish robust conclusions. The different technologies must be evaluated in comparison to competing methods of recycling and in the context of the system conditions that will change over the long term. The prospects for pyrolysis would appear to be improving due to the decarbonisation of the energy system. The substitution relationship to avoid the use of brown coal in the cement industry is of key significance for the overall picture and must be analysed in greater depth in the context of the structural change as a whole in the industrial sector.

In conclusion, it can be stated that the assumptions and expectations regarding the positive prospects for chemical recycling have been confirmed in essence as a justification for further investigation and development of pyrolysis procedures as a recycling route for plastic waste. No categorical show stoppers have been identified.

7.2 Conclusions

The results of the work undertaken as part of this discussion paper have confirmed the original assumptions of and motivation for the review. The conclusion is thus drawn that addressing the open questions and additional issues in an in-depth follow-up study would be justified and worthwhile.

The following points are considered to be relevant in this context (see Figure 13):

In-depth assessment of technology

- Detailed technical analysis and assessment of the processes and development work (e. g. through more extensive analysis of the literature, interviews with experts, inspections of plants, etc.)
- Selection and description of possible prototype plant configurations for plastic pyrolysis (in the sense of a "target process")
- Evaluation of the relevant technical and economic parameters of pilot, demonstration and commercially viable plants based on comparative figures from the literature and internal calculations
- Identification and description of the potential products, modes of operation and yields (basis for analysing intrinsic economic value)
- Determination and specification of the R&D requirements

Scenario analysis for future plastic waste streams

- Detailed analysis of the content of plastic waste and the estimated mixture of substances in individual sub-streams (literature research, potential assessment of sorting trials, etc.)
- Identification of political/socio-economic influencing factors and conditions, and assessment of the future availability of plastic waste (e. g. depending on packaging regulations, consumer behaviour in the future, technical advances in sorting/processing technology, etc.)
- Evaluation of costs and availability in terms of time and space (logistics, etc.)

Broadening and deepening the ecological assessment (LCA

- Specification of the substitution and competitive relationships
- Dynamisation of the system parameters (scenario analyses 2030-2050)

Analysis and assessment of the various uses of pyrolysis products

- Technical assessment of the possible plant configurations and foreseeable product mixes for pyrolysis
- Identification of potential sales channels in the basic chemicals sector (incl. logistics)
- Economic assessment

Analysis of policy and market conditions

- Summary of the relevant regulations and market conditions
- Evaluation and assessment of foreseeable developments and potential trends (e. g. in view of the EU's circular economy initiatives)
- Discussion of the acceptance and creditability of chemical recycling options

Development of a "Chemical recycling of plastic in NRW" strategic roadmap

- Identification of areas in need of development and action
- Definition of measures and timetable for implementing development and pilot projects in NRW

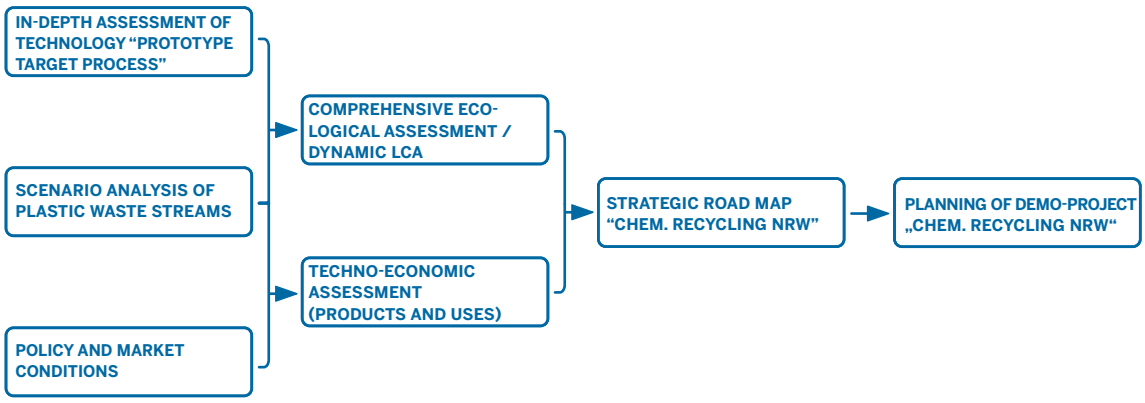

Figure 13: Overview of the key elements of the proposed follow-up study.

It is proposed that a follow-up study should be carried out in collaboration with science and industry, e. g. as part of the IN4climate.NRW initiative. The overall objective would be to work out and assess the strategic prospects of a demonstration plant for thermochemical recycling of plastic waste in NRW in order to contribute to ecological structural change in the state.

In terms of depth of analysis, quality requirements and outlay, this next step clearly goes beyond the scope of this discussion paper and will therefore require appropriate funding

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9. APPENDICES

9.1 Overview of classification according to TRL (Technology Readiness Level)

Rough classification	**Refined classification**
Basic research	TRL 1 – Basic principles observed and described, potential applications feasible
Development of Technology	TRL 2 – Description of a technology design and/or application
	TRL 3 – Basic evidence of functionality of individual components of an application/type of technology
	TRL 4 – Basic evidence of functionality of technology/application in the laboratory
Demonstration	TRL 5 – Evidence of functionality in environment relevant to application
	TRL 6 – Verification using demonstrator in environment relevant to application
	TRL 7 – Prototype test in operational environment
	TRL 8 – Qualified system with evidence of functional efficiency in operational environment
Commercialisation	TRL 9 – Successful commercial implementation of the system

Figure Appendix 1: Overview of classification according to TRL.

9.2 Operational features of thermochemical processes

- **Source of the energy utilised:** autothermal (internal supply of energy by means of exothermic partial reactions, particularly partial oxidation) allothermal (external energy supply)
- **Type of energy supply in allothermal processes:** indirect heat transfer (by means of heated walls or hot auxiliary media), mechanical energy (frictional heat), electric arcs
- **Target products of the decomposition process:** e. g. monomers, oligomers, low-molecular C-H fragments, synthesis gas (CO, H_2)
- **Additional reactants:** water vapour (-> e. g. reforming), oxygen (-> partial oxidation), carbon dioxide (-> CO-formation)
- **Auxiliary materials:** catalysts, fluidising agents (e. g. oil, sand), inert gases
- **Temperature** of the decomposition reaction
- **Holding time** of the substances and products at the high temperature range (e. g. fast to slow pyrolysis, carbonisation)

- **Heating rate**
- **Phase state and flow control** (e. g. fixed-bed, fluidised-bed, circulating fluidised-bed, entrained flow reactor, transported-bed reactor)
- **Flash:** on the one hand, "Flash" refers to the flash evaporation of liquids heated to a very high temperature; on the other hand, is also generally used for high speed processes, e. g. in the expression "flash point" (i. e. combustion point, the lowest temperature at which a vapour-air mixture forms on the surface of a flammable liquid, which can show a rapid propagation of flame if externally ignited). Names of specific processes, which may also be copyright protected, include further indications on the conditions of the process. For example: "ablative flash pyrolysis" (ablation: removal of material by heating, flash: (in this case) flash evaporation), "catalytic depolymerisation". Other names of specific processes are neutral in this respect (e. g. the "Hamburg pyrolysis process").

9.3 Advantages and disadvantages of the methods of chemically recycling plastic

Table 5 shows a comparison of the different technologies for chemical recycling with a summary of their advantages and disadvantages.

Table 5: Advantages and disadvantages of the methods of chemically recycling plastic (Source: Lechleitner et al. 2019).

	Advantages	Disadvantages
Solvolysis	Highly selective towards special polymers Monomers directly for further plastic synthesis	Complex to remove and handle solvent
Pyrolysis	Wide application of products Less sensitive to heteroatoms (no catalyst) High energy content of products Simple system design	Less selective – wide range of products Product processing is complex Chemically bonded heteroatoms can be problematic depending on application Energy input for endothermic reactions Tendency to carbonise
Thermal catalytic cracking	Wide application of products Product range controllable to some extent Lower heating requirement due to catalyst	Catalyst sensitive to special heteroatoms Technical process of catalyst separation is complex Tendency to carbonise
Hydrocracking	Lower coke formation due to hydrogen More stable, saturated products Lower thermic energy requirement due to exothermic hydration	Energy required for hydrogen supply Complex system technology
Gasification	Little preparation for use required Highly versatile product gas	Low molecular products, Oxygenation and therefore reduced value of products

9.4 Proportion of plastic by waste code number

Table Appendix 1: Proportion of plastic by waste code number (Source: Steger et al. 2018).

All waste categories that are classified as hazardous in the European Waste Catalogue (EWC) are marked with an asterisk (*) following the waste code number.

ASN	Designation	Plastic content	Source
020104	Plastic waste (without packaging)	100.00%	u.e.c. Berlin e.A.
030305	De-inking sludge from paper recycling	5.00%	B+T Group (2015), Trumpf et al. (2007) IPA (2015)
030307	Mechanically separated waste from pulping waste paper and cardboard	25.00%	Flamme (2002)
030308	Waste from sorting paper and cardboard for recycling	25.00%	Flamme (2002)
030310	Fibre rejects, fibre-, filler- and coating-sludges from mechanical separation	5.00%	B+T Group (2015), Trumpf et al. (2007), IPA (2015)
040209	Waste from composite materials (impregnated textiles, elastomer, plastomer)	100.00%	u.e.c. Berlin e.A.
040221	Waste from unprocessed textile fibres	66.00%	Wagner et al. (2012)
040222	Waste from processed textile fibres	66.00%	Wagner et al. (2012)
070213	Plastic waste	100.00%	u.e.c. Berlin e.A.
080111 *	Waste paint and varnish containing organic solvents or other dangerous substances	33.00%	IPA (2015)
080112	Waste paint and varnish other than those mentioned in 08 01 11	55.00%	IPA (2015)
080115 *	Aqueous sludges from paint or varnish containing organic solvents or other dangerous substances	5,00%	IPA (2015)
080116	Aqueous sludges containing paint or varnish varnish other than those mentioned in 08 01 15	5.00%	IPA (2015)
080117 *	Waste from paint or varnish removal containing organic solvents or other dangerous substances	5.00%	IPA (2015)
080118	Waste from paint or varnish removal other than those mentioned in 08 01 17	50,00%	Wagner et al. (2012)
080121 *	waste paint or varnish remover	50.00%	Wagner et al. (2012)
080409 *	Waste adhesives and sealants containing organic solvents or other dangerous substances	50.00%	Wagner et al. (2012)
080410	Waste adhesives and sealants other than those mentioned in 08 04 09	33.00%	IPA (2015)
080413 *	Aqueous sludges containing adhesives or sealants and containing organic solvents or other dangerous substances	55.00%	IPA (2015)
080414	Aqueous sludges containing adhesives or sealants other than those mentioned in 08 04 13	5.00%	IPA (2015)

ASN	Designation	Plastic content	Source
090110	Single use cameras without batteries	92.00%	Wagner et al. (2012)
090111 *	Single use cameras containing batteries included in 16 06 01, 16 06 02 or 16 06 03	80.00%	Wagner et al. (2012)
090112	Single use cameras containing batteries other than those mentioned in 09 01 11	80.00%	Wagner et al. (2012)
120105	Plastic shavings and turning chips	100.00%	u.e.c. Berlin e.A.
150102	Plastic packaging	100.00%	u.e.c. Berlin e.A.
150105	Composite packaging	21.00%	FKN (2015)
15010600	Undifferentiated mixed packaging	23.90%	Dehne (2015), Hoffmann et al. (2011)
15010601	Light-weight packaging (LWP)	44.40%	u.e.c. Berlin e.A., Hoffmann et al. (2011)
150109	Textile packaging	50.00%	Wagner et al. (2012)
150110 *	Packaging containing residues of dangerous sutstances or contaminated by dangerous substances	23.90%	Dehne (2015), Hoffmann et al. (2011)
150202 *	Absorbents, filter materials (including oil filters not otherwise specified), wiping cloths, protective clothing contaminated by dangerous substances	50.00%	Wagner et al. (2012)
150203	Absorbents, filter materials, wiping cloths and protective clothing other than those mentioned in 15 02 02	50.00%	Wagner et al. (2012)
160103	End-of-life tyres	27.00%	VCS (2003)
160104 *	End-of-life vehicles	20.00%	Schäfer (2004), VKE (2003),
160106	End-of-life vehicles, containing neither liquids nor other hazardous components	20.00%	Schäfer (2004), VKE (2003),
160119	Plastics	100.00%	u.e.c. Berlin e.A.
16012200	Components not otherwise specified	50.00%	Wagner et al. (2012)
16012202	Non-metallic components	50.00%	Wagner et al. (2012)
160209 *	Transformers and capacitors containing PCBs	25.00%	FGU (2009)
160210 *	Discarded equipment containing or contaminated by PCBs other than those mentioned in 16 02 09	20.00%	VKE (2003), Wagner et al. (2012), BDE, LfU Bayern (2001)
160211 *	Discarded equipment containing partially and fully halogenated chlorofluorocarbons	20.00%	VKE (2003), Wagner et al. (2012), BDE, LfU Bayern (2001)
160212 *	Discarded equipment containing free asbestos	20.00%	VKE (2003), Wagner et al. (2012), BDE, LfU Bayern (2001)

ASN	Designation	Plastic content	Source
160213 *	Discarded equipment containing hazardous components 22) other than those mentioned in 16 02 09 to 16 02 12	20.00%	VKE (2003), Wagner et al. (2012), BDE, LfU Bayern (2001)
160214	Discarded equipment other than those mentioned in 16 02 09 to 16 02 13	20.00%	VKE (2003), Wagner et al. (2012), BDE, LfU Bayern (2001)
160215 *	Hazardous components removed from discarded equipment	20.00%	VKE (2003), Wagner et al. (2012), BDE, LfU Bayern (2001)
16021500*	Undifferentiated hazardous components removed from discarded equipment	20.00%	VKE (2003), Wagner et al. (2012), BDE, LfU Bayern (2001)
16021501*	Waste containing mercury	10.00%	IPA (2015)
16021502*	Printed circuit boards	7.00%	VKE (2003)
16021503*	Toner cartridges	90.00%	Wagner et al. (2012)
16021504*	Plastics containing brominated flame retardants	100.00%	u.e.c. Berlin e.A.
16021509*	External power lines	50.00%	Kettler
160216	Components removed from discarded equipment other than those mentioned in 16 02 15	50.00%	Wagner et al. (2012)
16021601	External power lines (including cables)	50.00%	Kettler
160601 *	Lead batteries	10.00%	IPA (2015), GRS (2009)
160602 *	Ni-Cd-batteries	5.00%	IPA (2015), GRS (2009)
160603 *	Batteries containing mercury	10.00%	IPA (2015), GRS (2009)
160604	Alkaline batteries (except 16 06 03)	10.00%	IPA (2015), GRS (2009)
160605	Other batteries and accumulators	5.00%	IPA (2015), GRS (2009)
170203	Plastic	100.00%	u.e.c. Berlin e.A.
170204 *	Glass, plastic and wood containing or contaminated by dangerous substances	5.90%	Wagner et al. (2012)
170410 *	Cables containing oil, coal tar and other dangerous substances	43.10%	Schäfer (2004)
170411	Cables other than those mentioned in 17 04 10	43.10%	Schäfer (2004)
170603 *	Other insulation materials consisting of or containing dangerous substances	10.00%	IPA (2015)
170604	Insulation materials other than those mentioned in 17 06 01 and 17 06 03	10.00%	IPA (2015)
170901 *	Construction and demolition wastes containing and mercury	5.10%	Görisch (2007)

ASN	Designation	Plastic content	Source
170902 *	Construction and demolition wastes containing PCBs (e. g. PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, PCB-containing capacitors)	5.10%	Görisch (2007)
170903 *	Other construction and demolition wastes (including mixed waste) containing dangerous substances	5.10%	Görisch (2007)
170904	Mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03	5.10%	Görisch (2007)
180103 *	Wastes subject to special collection and disposal requirements in order to prevent infection	24.00%	IPA (2015), Wagner et al. (2012)
180104	Wastes not subject to special collection and disposal requirements in order to prevent infection (e. g. dressings, plaster casts, linen, disposable clothing, diapers)	34.30%	IPA (2015), Wagner et al. (2012)
180202 *	Wastes subject to special collection and disposal requirements in order to prevent infection	24.00%	IPA (2015), Wagner et al. (2012)
180203	Wastes not subject to special collection and disposal requirements in order to prevent infection	24.00%	IPA (2015), Wagner et al. (2012)
190209 *	Solid combustible wastes containing dangerous substances	34.00%	IPA (2015)
19029950	Products	25.00%	Wagner et al. (2012)
190501	Non-composted fraction of municipal and similar waste	30.00%	u.e.c. Berlin e.A.
191003 *	Fluff-light fraction and dust containing dangerous substances	52.50%	Reinhardt (2004,)Wagner et al. (2012)
191004	Fluff-light fraction and dust other than those mentio-ned in 19 10 03	52.50%	Reinhardt (2004), Wagner et al. (2012)
191204	Plastic and rubber	100.00%	u.e.c. Berlin e.A.
191208	Textiles	66.00%	Wagner et al. (2012)
191210	Combustible waste (refuse derived fuel)	42.00%	u.e.c. Berlin e.A.
191211 *	Other wastes (including mixtures of materials) from mechanical treatment of waste containing dangerous substances	8.00%	u.e.c. Berlin e.A.
191212	Other wastes (including mixtures of materials) from mechanical treatment of waste other than those mentioned in 19 12 11	8.00%	u.e.c. Berlin e.A.
200110	Clothing	40.00%	Wagner et al. (2012)
200111	Textiles	66.00%	Wagner et al. (2012)
200121 *	Fluorescent tubes and other waste containing mercury	16.70%	Obermoser et al. (2008)
200123 *	Discarded equipment containing chlorofluorocarbons	23.00%	Wagner et al. (2012)

ASN	Designation	Plastic content	Source
200133 *	Batteries and accumulators included in 16 06 01, 16 06 02 or 16 06 03, and unsorted batteries and accumulators containing these batteries	10.00%	IPA (2015), GRS (2009)
200134	Batteries and accumulators other than those mentioned in 20 01 33	10.00%	IPA (2015),
200135 *	Discarded electrical and electronic equipment containing hazardous components 66) other than those mentioned in 20 01 21 and 20 01 23	20.00%	VKE (2003), Wagner et al. (2012), BDE, LfU Bayern (2001)
200136	Discarded electrical and electronic equipment other than those mentioned in 20 01 21, 20 01 23 and 20 01 35	20.00%	VKE (2003), Wagner et al. (2012), BDE, LfU Bayern (2001)
200139	Plastics	100.00%	u.e.c. Berlin e.A.
20030100	Undifferentiated mixed municipal waste	17.15%	Hoffmann et al. (2011), u.e.c. Berlin e.A.
20030101	Household waste, household-type commercial waste, combined collection by public refuse collection	15.00%	u.e.c. Berlin e.A., Wagner et al. (2012), Hoffmann et al. (2011)
20030102	Household-type commercial waste delivered or collected separately from household waste	23.90%	Dehne (2015), Hoffmann et al. (2011)
20030104	Organic waste	1.00%	Hoffmann et al. (2011), u.e.c. Berlin e.A.
200302	Waste from markets	8.10%	Beyer et al. (2004)
200307	Bulky waste	17.80%	Hoffmann et al. (2011), u.e.c. Berlin e.A., Hauer (2008), Baur (2003), Wagner et al. (2012)

IN4 CLIMATE .NRW

Contact: **IN4climate.NRW**
Munscheidstraße 14
45886 Gelsenkirchen
GERMANY
+49 209 40 85 99-0
post@in4climate.nrw
www.in4climate.nrw/en