Evaluation of pyrolysis with LCA – 3 case studies

According to ISO 14040:2006 and ISO 14044:2006

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List of Acronyms

ADP	Abiotic Depletion Potential
AP	Acidification Potential
APC	Air Pollution Control
CFF	Circular Footprint formula
CML	Centre of Environmental Science at Leiden
EF	Environmental Footprint
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
HFO	Heavy fuel oil
HVR	Heavy vacuum residue
ILCD	International Cycle Data System
JRC	Joint Research Center of the European Commission
ISO	International Organization for Standardization
kg	kilogram (metric unit of mass)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Polyethylene – low density
LHV	Lower heating value
MJ	Mega Joule (unit of energy)
MSWI	Municipal solid waste incineration
MPW	Mixed plastic waste
n/a	not applicable
NMVOC	Non-Methane Volatile Organic Compound
PEF	Product Environmental Footprint
PE-HD	Polyethylene – high density
POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
PS	Polystyrene
t	tonne (metric unit of mass)
transp.	transported

UBA	Umweltbundesamt (German Environmental Agency)
VOC	Volatile Organic Compound

Glossary

Life cycle

A view of a product system as “consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal” (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

“Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040:2006, section 3.2)

Life Cycle Inventory (LCI)

“Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 14040:2006, section 3.3)

Life Cycle Impact Assessment (LCIA)

“Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” (ISO 14040:2006, section 3.4)

Life cycle interpretation

“Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” (ISO 14040:2006, section 3.5)

Functional unit

“Quantified performance of a product system for use as a reference unit” (ISO 14040:2006, section 3.20)

Allocation

“Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14040:2006, section 3.17)

Closed-loop and open-loop allocation of recycled material

“An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.”

“A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.”

(ISO 14044:2006, section 4.3.4.3.3)

Foreground system

“Those processes of the system that are specific to it … and/or directly affected by decisions analysed in the study.” (JRC, 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background system

“Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good….” (JRC, 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

“Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment” (ISO 14044:2006, section 3.45).

Executive Summary

Plastics have had a central place in people's lives since the middle of the last century, and have helped improve living standards, hygiene and nutrition around the world. However, in recent years, the management and disposal of used plastic has become recognised as a global environmental challenge.

For plastics to continue to be accepted in the marketplace it is important that appropriate technologies are developed and deployed that can effectively manage the waste plastic that arises at end of life. These technologies should maintain as much value in the material as possible, in line with the principles of the circular economy.

This study focuses on pyrolysis as chemical recycling technology, specifically, the approach taken by BASF in their "ChemCycling" project. Pyrolysis involves converting waste polymers back into chemical feedstock that can then be used to generate virgin-like polymers or fuels.

The main goal of the study is the environmental assessment of pyrolysis as part of the plastic value chain and comparison with established end of life options for plastic waste and with virgin production of basic chemicals.

The baseline for the LCA study is the anticipated situation in 2030 (considered "short-term" for sectoral developments) for waste management and pyrolysis technology in Germany with the focus on plastic waste from packaging. This 10-year timeframe is considered to be the minimum needed to develop large-scale (i.e. 100 – 300 kt per year) pyrolysis capacity. The results of the underlying study are based on data from a pyrolysis plant in commercial scale.

Three case studies have been undertaken, each with a different perspective, as listed below:

- Case study #1 – waste perspective
  The goal of this case study was to evaluate the environmental impacts of pyrolysis as end of life option for mixed plastic waste and compare against alternative waste management options including municipal solid waste incineration (MSWI) and refuse derived fuel (RDF). Only the waste processing activities have been assessed with the starting point where waste is collected for treatment (i.e. gate-to-grave scope).

- Case study #2 – product perspective: virgin-grade quality
  The goal of this case study was to evaluate the environmental impacts of pyrolysis as part of the value chain to produce an exemplary chemical product with virgin-grade quality and compare against production of an equivalent product via a conventional virgin polymer route. The scope of the study is up to the point at which the virgin-grade quality product is manufactured. The avoided burdens from not having to dispose of the mixed plastic waste (MPW) by 30% MSWI/70% RDF are considered within the assessment.

- Case study #3 – product perspective: various qualities of plastic products
  The goal of this case study was to consider the full life cycle of a mix of three commodity plastics (PE, PP, PS) in Germany in the year 2030. These are modelled as being produced from virgin polymers and undergo different treatment options at end of life (pyrolysis, mechanical recycling or MSWI).

Case study #1 – waste perspective

Compared to alternative end of life options comprising 100% MSWI, 100% RDF and a mix of 30% MSWI/70% RDF, pyrolysis has got a clear superior performance for climate change impact.

Although the MSWI and RDF based disposal routes receive significantly greater credits than those for recycling, these are more than outweighed by the much greater emissions from combustion of the plastic waste.

Pyrolysis is also the preferred technology for impacts associated with resource use, energy carriers. The energy consumption of the pyrolysis process is significantly greater than that for MSWI or RDF, but this is more than compensated for by the much greater credits obtained from material substitution than from energy substitution in the incineration processes.

However, for other environmental impacts assessed in this study (acidification terrestrial and freshwater, eutrophication freshwater and marine, photochemical ozone formation), the MSWI and RDF technologies outperform pyrolysis as they receive greater credits from energy recovery than are received from the products of pyrolysis.

A selection of scenario analyses was carried out to test the influence on the climate change results of changing assumptions in the LCA model.

- The level of decarbonisation of the energy mix has a large impact on the credits received by the MSWI and RDF processes. A fully decarbonised energy mix results in much higher impacts for these processes as fewer credits are received from energy recovery. In contrast a fossil-heavy energy mix, boosts these credits to the point where these methods may become preferred over pyrolysis.
- Changing assumptions about the economic value of different waste streams in the sorting plant or of expending additional effort to make cleaner waste streams in the sorting plant have a negligible influence on the results of the study.
- Assumptions relating to the purification efficiency of pyrolysis oil also do not have a very significant impact on the results.
- In contrast, the results are very sensitive to changing assumptions around pyrolysis efficiency. Increasing this efficiency from 71% to 77% and 87% results in reductions in climate change burdens of 27% and 69% respectively.
- A final scenario considered an additional waste treatment route and looked at the use of MPW in cement kilns. If MPW is replaced by other alternative fuels (such as waste tyres, waste oil, animal fat, mixed fractions of municipal waste, solvents, sewage sludge, oil sludge, organic distillation residues etc.) the burdens from the cement kiln become much greater than for pyrolysis. However, if MPW replaces lignite, the results switch, and the cement kiln looks much better than pyrolysis.

Case study #2 – product perspective: virgin-grade quality

Virgin grade LDPE produced from pyrolysis oil from pyrolysis according to the mass balance principle shows significant climate change benefits compared to that produced from fossil-based naphtha. The impacts from the pyrolysis process itself are higher than those for production from naphtha. However, pyrolysis diverts waste from other treatment methods. When the avoided burden from not sending this waste to 30% MSWI/70% RDF are accounted for, significant net credits are received that reduce the climate change impact of the pyrolysis route below that of the fossil-based naphtha route.

Pyrolysis also outperforms production from naphtha for resource use, energy carriers. In this case the process emissions from the pyrolysis process are ~40% lower than for virgin LDPE production.

For the other impact categories assessed in this study (acidification terrestrial and freshwater, eutrophication freshwater and marine, photochemical ozone formation), LDPE production from fossil-based naphtha feedstock is environmentally more favourable than the pyrolysis process. This is mainly due to high emissions in the energy recovery process which are only partly compensated for by prevented emissions due to incineration.

Scenario analyses were carried out to test the influence on the climate change results of changing assumptions in the LCA model.

- Assumptions relating to the energy credits received from the avoided MSWI/RDF waste treatment route have a large impact on the results of this case study. The baseline assumption assumed a credit for the predicted 2030 energy mix in Germany. However, if recovered electricity substitutes electricity from a lignite power plant and recovered heat substitutes thermal energy based on heavy fuel oil (HFO), then the climate change impact of pyrolysis increases greatly. This may be representative of the mid-term future for parts of eastern Europe. However, in the alternative case, where energy mixes are fully decarbonised, the pyrolysis route become much more favourable than the base-case. This may be representative of the mid-term future of countries with more sophisticated industrial and energy processes e.g. Scandinavian countries.
- A second scenario analysis examined the effects on the climate change results from increasing the burdens associated with sorting of the MPW prior to pyrolysis. This had a negligible influence on the results of the study.

Case study #3 – product perspective – various qualities of plastic products

While case study #2 focuses on virgin-grade-quality products, case study #3 covers plastic products with a lower quality level. The system under study was the production and EoL treatment of a mix of three commodity plastics (PE, PP, PS) in Germany in the year 2030. The plastics were all produced from fossil-based precursors but sent to three different waste treatment routes at end of life (pyrolysis, mechanical recycling or incineration comprising 30% MSWI, 70% RDF), providing products with different quality levels. The Circular Footprint Formula (CFF), developed by the European Commission (2018), was selected as the method for evaluating these differences in quality.

The results of the assessment vary a lot based on the impact category selected.

- For climate change impact, there is no significant difference between pyrolysis and mechanical recycling at end of life. In contrast, the incineration treatment option shows much higher burdens for this impact category.
- Chemical and mechanical recycling also show similar results for acidification and photochemical ozone creation, although incineration is the preferred waste treatment option for these impact categories as it receives very large credits from recovered energy.
- For eutrophication, pyrolysis shows higher burdens than mechanical recycling, although, again, incineration is the preferred choice.
- For resource use, energy carriers, all three routes have similar impacts.

Scenario analyses were carried out to test the influence on the climate change results of changing assumptions in the LCA model.

- As with case study #1, the level of decarbonisation of the energy mix a large impact on the credits received by the incineration waste management route. A fully decarbonised energy mix results in higher impacts for incineration as fewer credits are received from energy

recovery. In contrast a fossil-heavy energy mix boosts these credits to the point where this route become preferred over both chemical and mechanical recycling.

- Variations in recyclate quality obtained from the mechanical recycling route also leads to moderate changes in the results.
- Further scenario analyses examined how changes in energy consumption and material losses influence the performance of the mechanical recycling route. Changes in energy consumption of +/-30% were seen to have negligible consequences.
- Changes in material efficiency in a similar range (increased by +37%, decreased by -30%) have a moderate influence.
- The combination of recyclate quality and material efficiency leads to a significant influence on the greenhouse gas emissions for the mechanical recycling system which significantly influences the comparison of these results with those of the pyrolysis technology.
- Variations in the CFF factors A (allocation factor of burdens and credits between supplier and user of recycled materials) and B (allocation factor of energy recovery processes: it applies both to burdens and credits) result in only modest changes to the results.

Overall, the results of this study show that pyrolysis can serve as a high value waste management option regarding climate change and material efficiency. As reported above, in two case studies (#1 and #2) assessed in this report, pyrolysis was shown to be the preferred option regarding climate change impact and resource use. For example, pyrolysis is preferred over incineration as an end of life treatment route of mixed plastic waste and is also preferred over fossil-based naphtha for production of virgin-grade plastic feedstock. Furthermore, the results show that there is no significant difference in climate change results for recycled plastic products from pyrolysis and mechanical recycling.

The energy credits given for incineration processes can have a large influence on the climate change results. These credits are sensitive to the composition of the grid mix. It is reasonable to expect that the general trend will be towards grid mixes with an increased share of renewable energy. Scenario analyses showed that higher rates of decarbonisation in grid mixes lead to higher overall climate change values due for incineration routes due to decreased credits at end of life. This means that, over time, the relative benefits of pyrolysis compared to incineration technologies are likely to increase even further.

For other impact categories such as acidification and eutrophication, pyrolysis shows disadvantages as an end of life treatment method compared to incineration, due to the high credits that incineration received for recovered energy.

Similarly, case study 2 shows, when producing plastics using pyrolysis or fossil-based naphtha routes, pyrolysis is preferred for climate change and resources use, but is less favoured for acidification, eutrophication and photochemical ozone formation.

The study gives an overview on environmental impacts linked to different technologies which are applying mixed plastic waste as feedstock. Significant variations in results have been observed for mechanical recycling due to material efficiency and quality of recyclates. Regarding climate change, both pyrolysis and mechanical recycling can have beneficial or adverse effects depending on the application case (quality and composition of waste, application case of products). The respective beneficial application cases (combination of product application and waste fraction) would have to be assessed in specific LCA studies. It has been a decision of the authors to not model these as it would be going beyond the scope of the present study. So, depending on the specific application case, both technologies could be considered as complementary technical solutions for the use of mixed plastic waste rather than competitive in terms of environmental impact.

This means that there is no out-right preferred technology for either treating waste or manufacturing plastics, rather, this will depend upon the impact category that is being assessed. However, looking at current and future global environmental challenges, global warming and challenges around the transition from linear to circular economy are, and will be, crucial for sustainable business and production practices. On these key measures, pyrolysis is shown to have the potential to realize benefits in the future.

The quality of the results is strongly correlated to the quality of data used for calculation of the results. In this study, assumptions and approximations had to be made for certain important parameters (e.g. the purification and pyrolysis steps in the pyrolysis process). Collecting more precise data on these processes would lead to more robust and transparent results.

1. Introduction

1.1. Current situation with plastic waste

Plastics have been part of everyone's life for decades and have helped improve living standards, hygiene and nutrition around the world. However, in recent years, the management and disposal of used plastic has become recognised to be a global environmental challenge.

Some plastic waste facts to set the scene for this study (Alliance to end plastic waste, 2019):

- 150-200 Mio. tonnes plastic waste is generated worldwide each year;
- Plastic waste generation is expected to double in the next 15 years;
- Improper waste management leads to significant leakage into oceans and seas – approximately 8 Mio. tonnes per year globally;
- 80% of ocean plastic comes from land-based applications;
- Replacing plastics in packaging and consumer products with alternative materials could raise environmental costs nearly fourfold;
- There is an untapped value in post-use plastic that can be used to incentivize collection and reprocessing.

Annual data from 2017 published in the "Plastikatlas 2019" (BUND und Heinrich Böll Stiftung, 2019) display the situation regarding post-consumer plastic waste in Germany:

- 5,2 Mio tonnes of plastic waste in total (post-consumer);
    - Sources are commercial and municipal waste;
- 3,15 Mio. tonnes of plastic waste treated as waste-to-energy – in municipal solid waste incineration (MSWI) or in refuse derived fuel (RDF);
- 1,23 Mio tonnes of plastic waste input to mechanical recycling;
    - 900,000 tonnes of recyclate is produced;
    - This equates to about 73% material efficiency for mechanical recycling in average - plastic waste that arises during the recycling process that cannot itself be recycled, is sent for recovery as waste-to-energy.
- Significant quantities of plastic waste are exported to foreign countries;
- 50,000 tonnes are recycled into feedstock.

Data from Umweltbundesamt for post-consumer plastic waste in Germany in 2017 are very similar. The total amounts of post-consumer plastic waste generated in the European Union as a whole in 2016 are as follows (Umweltbundesamt, Kunststoffe in der Umwelt, 2019):

- 27,1 Mio tonnes of plastic waste in total (post-consumer);
    - 31,1% used for mechanical recycling
    - 41,6% used for waste-to-energy
    - 27,3% are landfilled

An analysis on plastic waste recycling in Germany in 2016 (Umweltbundesamt [Positionspapier], 2016) shows a high potential increase of lightweight packaging waste that could be used for material recycling. Most relevant plastic types identified in the study in the fraction “lightweight packaging waste” are PE and PP.

Referring to the waste hierarchy of the European Union (European Commission, Directive 2008/98/EC on waste ["Waste Framework Directive"], 2008), after the two preferred options, prevention of waste and preparing for re-use, recycling is the following choice followed by recovery and finally disposal.

This study evaluates the technology “pyrolysis” as one recycling option of plastic waste in comparison to established technologies to treat plastic waste, such as incineration and mechanical recycling.

1.2. Pyrolysis technology

The technology “chemical recycling” is not new — it has been used to turn plastic into fuel or feedstock for decades. But recently, industry is taking a fresh look at chemical recycling. The definition of chemical recycling (also called “feedstock recycling”) according to ISO 15270 (2008) is: “conversion of monomers or production of new raw materials by changing the chemical structure of plastic waste through cracking, gasification or depolymerization, excluding energy recovery and incineration.”

According to ISO 15270 (2008), there are four methods of chemical recycling, which are substantially different in terms of waste input and obtained products:

- *Depolymerization* turns mono-material plastic (e.g. PET bottles) back into monomers, which can be re-polymerized into new products.
- *Solvolysis* (dissolution) is used to break down certain plastics such as polyurethane into smaller parts with the aid of solvents.
- *Pyrolysis* converts mixed plastics into pyrolysis oil in an inert atmosphere, which can be cracked down and further refined for new plastics production.
- *Gasification* can process mixed plastic waste and turn it into syngas, which can be used to build larger building blocks for new chemicals.

The latter two — pyrolysis and gasification — transform plastics back into basic chemicals by thermal decomposition at elevated temperatures (> 500°C), where usually all the plastic additives and contaminants are also converted back into basic chemicals. To meet the same quality standards as virgin feedstock, an extra sorting step of mixed plastic waste and a purification step of the output material is necessary. When the resulting oil and gas are used for chemical production, e.g. in the BASF production Verbund (e.g. feedstock for the cracker), the final plastic products exhibit the same performance to those produced from virgin feedstock.

This study focuses on the pyrolysis technology with the feedstock “mixed plastic waste” (abbreviation: MPW) and the resulting product “purified pyrolysis oil”.

1.3. Background and superior target of the study

BASF is working on improving the recyclability of plastic waste and thus helping to create a circular economy. One way that BASF is contributing is the so called “ChemCycling” project. “ChemCycling” is the BASF internal project term for feeding pyrolysis oil - produced from mixed plastic waste in the pyrolysis technology – into the production Verbund, thereby partially replacing fossil primary resources.

BASF started its ChemCycling project in 2018 with the aim to process recycled raw materials obtained from plastic waste in its production Verbund. At the end of 2018, BASF first used pilot volumes of a pyrolysis oil derived from plastic waste as a feedstock in its own production (BASF, Trade News, July 2019, 2019). The goal for BASF is closing the gap in the waste management process to seize the benefits of a circular plastic economy.

The superior target for the study is the environmental assessment of pyrolysis as part of the plastic value chain by comparison with established end of life options for plastic waste and virgin production of basic chemicals.

The baseline for the LCA study is the anticipated situation in about 10 years from now on (baseline 2030, considered as “short-term” for sectoral developments) of the waste management and pyrolysis technology in Germany with the focus on plastic waste. The reason is that a large-scale pyrolysis capacity (capacity for BASF use: 100-300 kt of pyrolysis oil per year) needs to be first build up in the next 10 years.

Steam crackers usually have a capacity of 1-2 Mio t per year. If 300 kt/a pyrolysis oil would be used as cracker feed, then only part of the total cracker feed would be substituted by pyrolysis oil. Currently, pyrolysis is running with post-consumer mixed plastic waste already at commercial scale with a plant capacity of 5-15 kt. For establishing 100 kt capacity in Germany roughly 10 plants would have to be built.

1.4. Setup of the study

The study is divided in three LCA case studies, which investigate the pyrolysis from different perspectives in comparison to selected alternative technologies respectively. The setup of different case studies considers that pyrolysis is not only an end of life option for plastic waste but also generates a feedstock to produce virgin-grade plastics.

So, the study report is divided in three LCA studies:

- Section 2: Case study #1 – *plastic <u>waste</u> perspective*
    - Goal and Scope definition
    - Life Cycle Inventory
    - LCIA results
- Section 3: Case study #2 – *plastic <u>product</u> perspective - virgin-grade quality*
    - Goal and Scope definition
    - Life Cycle Inventory
    - LCIA results
- Section 4: Case study #3 – *plastic <u>product</u> perspective - various qualities of plastic products*
    - Goal and Scope definition
    - Life Cycle Inventory
    - LCIA results

Section 5 comprises a common interpretation part for all three case studies analysing the findings, the limitations, the data applied, the results and conclusions of the case studies.

2. Case study #1 – waste perspective

2.1. Goal of the Study

Reasons for carrying out the study

General reasons for carrying out the study which are applicable for all three case studies are described in section 1.3.

As first part of the study "Evaluation of pyrolysis with LCA", the case study #1 occupies the waste perspective. The goal of case study #1 is to evaluate the environmental impacts of pyrolysis as end of life option for mixed plastic waste. This includes the consideration of a clearly defined value of the resulting product(s). The baseline for the evaluation is the anticipated situation in 2030 in Germany.

Most common technical routes for treatment of plastic waste in end of life nowadays and anticipated to be still valid in 10 years in Germany are (for selection of comparative system):

- thermal treatment in municipal solid waste incineration plants (= "waste-to-energy"),
- thermal treatment in refuse derived fuel (RDF) plants,
- application in cement kilns as alternative fuel,
- mechanical recycling to produce plastic recyclate.

The majority of mixed plastic waste is currently incinerated either in MSWI or RDF plants (Umweltbundesamt, Analyse der Effizienz und Vorschläge zur Optimierung von Sammelsystemen der haushaltsnahen Erfassung von Leichtverpackungen und stoffgleichen Nichtverpackungen auf der Grundlage vorhandener Daten, Texte 37/2018, Mai 2018). As the RDF plants use the same technology as MSWI plants, this technology is not considered separately in the study.

The cement kiln application is assessed separately in a scenario in case study #1 including different possible settings. The application of mixed plastic waste as one of numerous fuels does not allow a clearly defined parameter setup, so various options are analysed.

Mechanical recycling is mainly applicable for sorted mono-material fractions. Also, the quality or value of the recyclate (product of mechanical recycling) varies depending on the application (e.g. material substitute of wood or concrete), so that a proper definition of a substitute is arbitrary. Thus, this technology is considered as not eligible for case study #1. The quality aspect of resulting products from pyrolysis and other technical routes are assessed in case study #3.

Several scenarios are assessed to check the influence on the overall results of potential divergent developments compared to the baseline situation in the considered technologies. The scenarios are used as well to derive potential LCA results of the assessed systems both in relation to other European countries besides Germany and the future beyond 2040, with >20 years considered as "mid-term" related to sectoral developments.

Intended audience

The intended audience of the study are internal and external stakeholders in Europe regarding waste management, plastic waste treatment and circular economy in the chemical industry.

Intended application

The intended application of the study is to enrich the discussion about environmental evaluation of pyrolysis in the context of plastic waste recycling resp. end of life of plastic products with LCA-based data and results.

The results are intended to support comparative assertions and intended to be disclosed to the public The study has been conducted according to the requirements of ISO 14040 (ISO 14040, 2006) and 14044 (ISO 14044, 2006). The requirements of ISO/TS 14071 (2014) are respected.

2.2. Scope of the Study

The following sections describe the general scope of the case study #1 to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.2.1. System boundaries, Product Systems, Product Function(s) and Functional Unit

The function of the product system is the treatment of mixed plastic waste (MPW) in 2030 in Germany. The defined system includes the collection of mixed waste from households in Germany (system of yellow bag/bin), the sorting of that waste with focus on MPW as the target waste fraction and its further treatment.

Two selected treatment technologies for MPW have been assessed:

- pyrolysis as the basic system, and
- a combination of 30% MSWI and 70% RDF as a comparative system.

The functional unit is defined as *the treatment of one tonne of mixed plastic waste (MPW).*

Accordingly, the corresponding reference flow is one tonne of MPW.

The function and functional unit are consistent with the stated goals of the study.

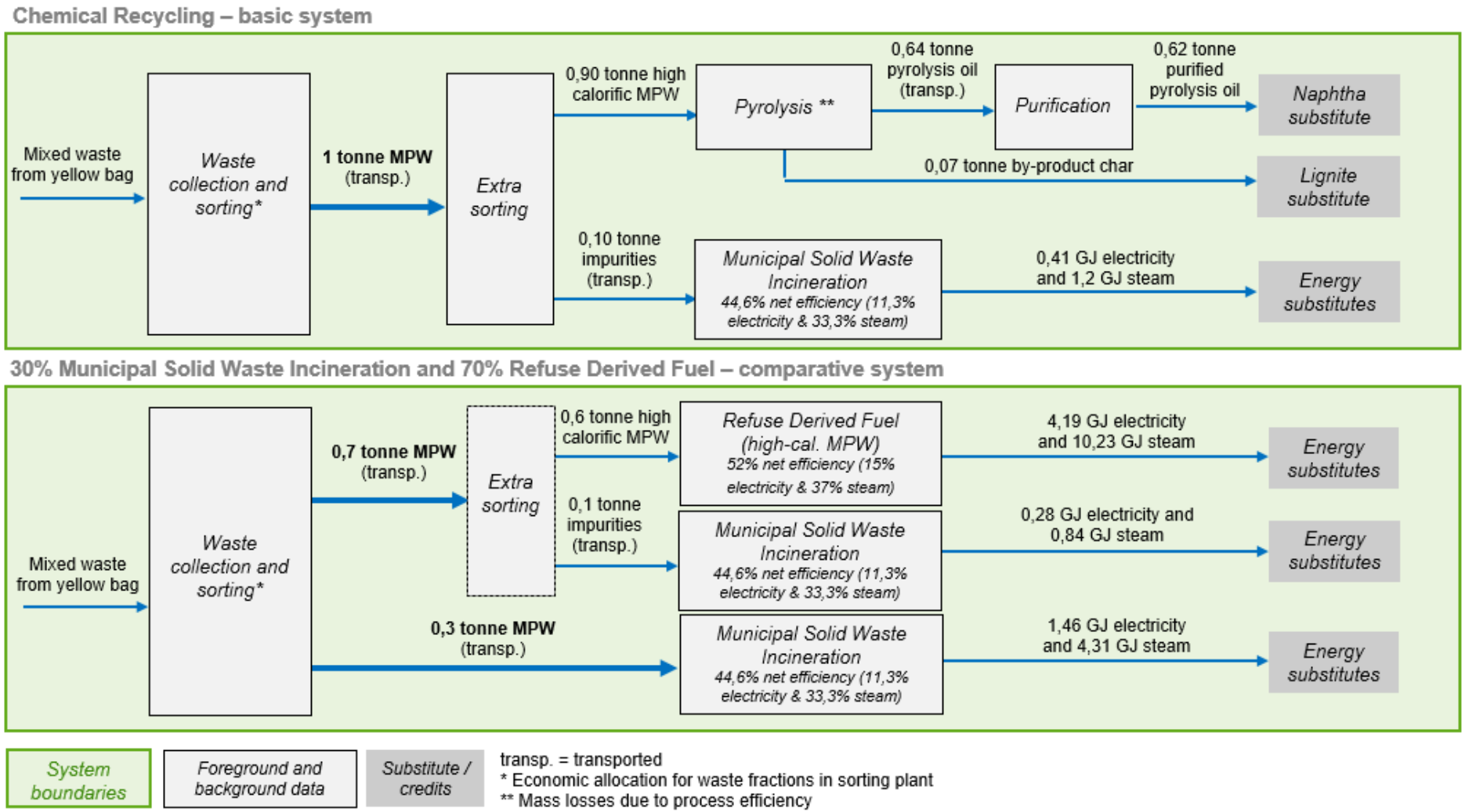


Figure 2-1 System boundaries – case study #1

The system boundaries of the basic system and comparative system are shown in Figure 2-1.The complete systems, including the system expansion due to material and energy substitution, are displayed. Whenever transportation of materials or intermediates takes place, this is indicated next to the substance name in the system boundaries ("transp."). The type of transportation and assumed distances are described in the Life Cycle Inventory Analysis (section 2.3).

Inclusions and exclusions are summarised in the following table.

Table 2-1: Inclusions and exclusions in system boundaries - case study #1

Included		Excluded	
✓	Mixed waste collection and transportation to sorting plant	×	Capital goods
✓	Mixed waste sorting	×	Infrastructure
✓	MPW transport to extra sorting resp. MSWI	×	Employee commute
✓	MSWI technology with energy recovery (both for high-calorific waste and municipal waste)	×	Any administrative activities
✓	Pyrolysis technology with 1 main product and 1 by-product	×	Baling press at mixed waste collection plant
✓	Transport of pyrolysis oil to purification		
✓	Purification of pyrolysis oil		
✓	Material substitution of naphtha		
✓	Energy/fuel substitution of lignite, electricity and thermal energy		

Production of capital equipment, infrastructure and impacts associated with employee commuting and administrative activities have been excluded as these should not be relevant when allocated to the quantities of waste being processed.

No data were available for the baling press but this is likely to be insignificant compared other emissions from waste processing via either the base case or comparative scenario. In any case, this process would be applied to waste input to both assessed disposal routes and so does not introduce bias into the study.

The basic system and comparative system are equivalent in the following aspects:

- in the amount and type of waste (=product) that is treated - mixed plastic waste from sorting plant,
- in the system boundaries applied: starting with collection of waste at households and resulting products or energy carriers from selected technologies are credited by system expansion (material or energy substitution), and
- in the foreground and background data applied.

No functions associated with the different systems have been knowingly omitted from the study.

Table 2-2: Product systems assessed in case study #1

Case 1 - System	Short description
Basic system	The defined waste feedstock (MPW) is treated in a pyrolysis plant. Extra sorting of MPW is necessary to meet the feedstock requirements of the pyrolysis technology. Resulting pyrolysis oil undergoes a purification step. Purified pyrolysis oil is used as feedstock in chemical industry substituting naphtha from conventional (fossil-based) production.
Comparative system	The defined waste feedstock (MPW) is treated in a combination of 30% municipal solid waste incineration (MSWI) plant and 70% Refuse Derived Fuel (RDF) plant. The resulting energy (mix of thermal energy and electricity) is recovered and substitutes for thermal energy and electricity on the German market.

2.2.2. Description of the representativeness of the chosen products and systems

Definition of the baseline systems – situation in 2030 in Germany

The technical development from now until 2030 of the assessed technologies has been considered, and this chapter describes how this has been implemented in the case study to define the baseline in 2030.

Core technologies considered in the product systems

The pyrolysis technology is based on primary data provided by a commercial manufacturer based on 2018 data. The purification technology is based on primary lab-scale data from 2019. Both these technologies will be optimised over the next 10 years of development and operation. As such, the use of these data represents conservative assumptions in the context of the goal and scope of case study #1. Large quantities of plastic waste, but only a fraction of MPW, are treated in MSWI plants. It is expected, that the total amount of plastic waste will at least remain the same in 2030. Due to higher quotas, it is expected that the share of mechanical recycling will increase, but a large portion of MPW will be of low quality and would need to be disposed of by other means, including pyrolysis. Source: (Umweltbundesamt, Energieerzeugung aus Abfällen – Stand und Potenziale in Deutschland bis 2030, Texte /2018, Juni 2018, 2018)

- 6,2 Mio t of plastic waste in Germany
  - 2,1 Mio t treated in MSWI
  - 1,1 Mio t treated as RDF (all technologies: RDF incineration = MSWI with higher steam & electricity recovery rate, coal-fired plants, cement plants)
  - 2,8 Mio t treated in mechanical recycling

The MSWI technology is based on average secondary German industry data from 2018. In a study of the German Environment Agency (abbreviation “UBA”) from 2018 (Umweltbundesamt, Energieerzeugung aus Abfällen – Stand und Potenziale in Deutschland bis 2030, Texte /2018, Juni 2018, 2018) including a forecast for 2030, it is stated that in 2015 already optimised incineration plants in Germany will technically operate in a comparable way in 2030. It is deemed appropriate for case study #1 that the current technical data are applied for the anticipated situation in 2030.

The RDF technology is also relevant for the treatment of plastics waste in Germany. There is an indication that the MSWI technology is comparable to the RDF technology. As mentioned previously,

the MSWI is based on secondary data from UBA. UBA stated that in 2015 already optimised incineration plants in Germany will technically operate in a comparable way in 2030. It is deemed appropriate for case study #1 that the current technical data are applied for the anticipated situation in 2030.

It is indicated that RDF incineration plants and cement plants are relevant waste management technologies in Germany. Due to higher energy efficiency rates, it is expected that pyrolysis will rather compete with RDF incineration than with cement plants (Hoffmeister, 2016).

- 75 RDF plants in Germany
    - 40 RDF co-incineration (like cement plant & coal-fired plants),
    - 35 RDF incineration plants.

Incineration plant capacity in Germany in 2017 indicates that 30% of the packaging waste is treated in a municipal waste incineration plant and 70% in an RDF incineration plant (Umweltbundesamt, Umweltbundesamt auf Basis Arbeitsgemeinschaft Energiebilanzen: Energiedaten, Stand Dezember 2018, 2018). Based on this information a base case for 30% MSWI and 70% RDF has been evaluated in this study. Please see more information in Annex C:

Technologies considered in the product systems due to system expansion

Generation of electricity: political targets for the transformation of the German electricity production are set by the German Government for the next 30 years including intermediate targets, see (Federal Government of Germany, 2019). The 2030 electricity mix for Germany is modelled by interpolation of the current situation and the planned situation in 2038 resp. 2040. Most importantly, the nuclear power will be phased out by 2022, the share of coal-fired power plants will be significantly reduced by 2030, and the share of renewable power plants will be significantly increased. According to the plans of the German Government, the power plant capacity for coal-fired power plants will be reduced to 17 GW by 2030, which is 40% of the power plant capacity today. That corresponds to the assumed linear interpolation between 2019 and 2038.

Generation of thermal energy: the transformation of the German production of thermal energy is forecasted in an ExxonMobil study (ExxonMobil, 2018). The study predicts the energy market in 2040 in Germany. Based on this forecast the 2030 thermal energy mix for Germany is modelled by interpolation of the current situation and the anticipated 2040 situation. Most importantly, the share of fossil energy resources will be reduced, and the share of renewable energy resources will be increased.

Production of Naphtha: current data of naphtha produced for the German market is considered. As the production of naphtha is already optimised in 2018 and no major technical improvement are expected, it is deemed appropriate for case study #1 that the current technical data are applied for the anticipated situation in 2030.

Further technologies as part of the systems

Sorting plant: data has been sourced from Meilo sorting plant in Gernsheim, Germany, one of the most modern plants in Europa for sorting lightweight packaging (Kaitinnis, 2019) (UmweltMagazin, 2018). As the UBA study mentions (Umweltbundesamt, Energieerzeugung aus Abfällen – Stand und Potenziale in Deutschland bis 2030, Texte /2018, Juni 2018), the waste sorting technology will be improved significantly by 2030. However, it is deemed appropriate that one of the most modern sorting plants of 2019 will be representative for the average situation in Germany in 2030. The total electricity consumption of the Meilo plant is significantly higher than that of average sorting plants today.

Plant for extra sorting: data are estimated based on the Meilo sorting plant. Extra sorting divides the waste fraction “mixed plastic waste” in two different waste fractions: high-calorific mixed plastic waste and residual waste (“impurities”). The amounts are based on the composition of the extra sorted MPW fraction MK352 (please see section 0 for a definition).

Transportation: transport is undertaken with either diesel-driven trucks or electric-driven trains. To adopt the available 2018 data for transports to the 2030 situation is considered as suitable proxy because transportation is not the most relevant technology considered in the systems. However, the technical development of both trucks and trains will be most likely a further electrification combined with the already described transformation of the German electricity grid mix.

Definition of the baseline products – situation in 2030 in Germany

The current situation in Germany regarding waste management on a municipal level is based on “DerGrünePunkt” and “Duales System Deutschland (DSD)”. The contents of yellow bag and yellow bins - mixed waste with a high content of lightweight plastic packaging - are collected from the consumer households. It is assumed that the same system will be applied in 2030.

Description of selected target feedstock – mixed plastic waste (MPW):

The target feedstock is sourced from collected, transported and sorted mixed waste from households. The collection from “point of origin” (→ consumer households) of mixed waste as contents of yellow bag / yellow bin. The concept of “first responsibility” is applied: the system that produces products and the consequential waste carries all environmental burdens, this means that the mixed plastic waste sourced from yellow bags carries no environmental burden from previous system as plastic waste from yellow bag and bin is regarded as environmentally burden free. It is assumed that the mixed plastic waste from households has no relevant economic value.

This is true in 2019 and it is deemed appropriate for 2030 – however, for the comparison of the two assessed systems, there is no difference whether a burden for mixed waste is considered or not as both systems would carry the same extra environmental burden.

The target feedstock from currently operated sorting plants needs further processing/sorting to meet the requirements as feedstock of the pyrolysis technology, which is the generation of “high-calorific mixed plastic waste”. No further processing/sorting is needed for treatment in incineration plants.

Extra sorting divides the waste stream MPW in two different waste fractions: high-calorific mixed plastic waste and residual waste (“impurities”). The MPW division is also considered in the incineration systems to ensure the comparability of both assessed system, applying two different incineration technologies – waste incineration of high-calorific MPW and waste incineration of average municipal waste. The composition of MPW is considered comparable in 2019 and in 2030 in Germany.

The economic value of MPW is assumed to be 110€ per tonne in 2030 and is used to allocate burdens from the sorting plant (please see section 2.2.8). Nowadays, in 2018, the economic value of MPW is 0€ that is considered to be a conservative assumption as the disposal costs are estimated to 110 €/t. The economic value of mono-material plastic waste fraction is set to 228€ based on current values (EUWID, 2019). The resulting relation of economic values of MPW compared to mono plastic waste fractions with 50% is considered appropriate for the 2030 situation in Germany. The price effect for MPW in 2030 is based on anticipated competition in the plastic waste market. It is expected that the annual amounts of exported MPW from Germany (about 600.000 tonnes) will be significantly reduced.

The collection, sorting and processing steps of mixed waste from point of origin until the waste reaches the level “high-calorific mixed plastic waste” determines the environmental burden of the feedstock into pyrolysis technology. Same applies to the MSWI system excluding the efforts for extra sorting. The overall availability in Germany of MPW for pyrolysis in the future is considered to be high (CE Delft, 2019).

Figure 2-2 illustrates the waste streams for case studies #1 and #2.

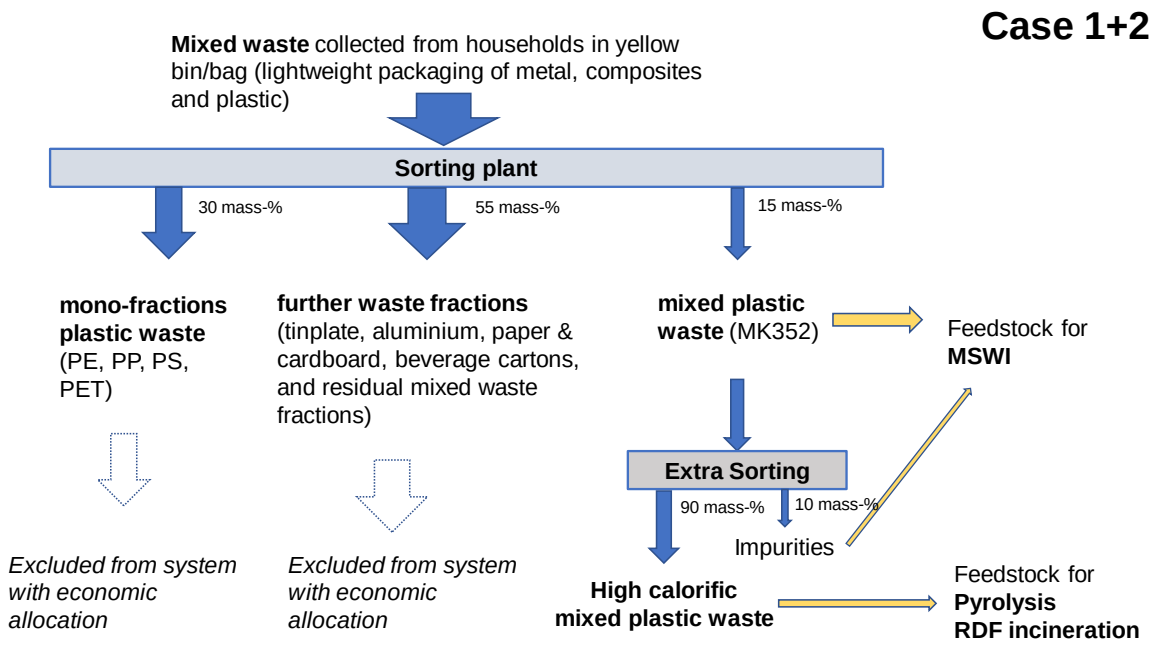


Figure 2-2 waste streams for case study #1+2

Description of further products in the systems

Fossil-based naphtha: naphtha is a common feedstock for plastics manufacture and is assumed to be the material substituted for by the purified pyrolysis oil output from pyrolysis. The LHV of naphtha on the German market is 44 MJ/kg. Naphtha is based on crude oil processed in a petroleum refinery. The dataset covers the entire supply chain - this includes well drilling, crude oil production and processing as well as transportation of crude oil via pipeline resp. vessel to the refinery and the complex refinery activities (conversion plants) including various products. This is a mature and well-optimised production process, so no significant changes are anticipated to occur by 2030.

Fossil-based heavy vacuum residue (HVR): HVR is modelled as an alternative material substitute in the system of pyrolysis in a scenario analysis. HVR is the residue from the second distillation step. It is based on crude oil processed in a petroleum refinery. Crude oil is heated and fed to a distillation unit at atmospheric pressure where it is vaporized and fractionated by condensing. The atmospheric distillation residue is heated and fed to a vacuum distillation unit for further separation at very low pressure. No relevant changes are anticipated to occur in this production process by 2030.

2.2.3. Key performance characteristics

Mixed plastic waste (MPW)

The waste fraction “MK352” (specification: (DerGrünePunkt, 2018)) has been selected as representative of MPW in the German waste system “DerGrünePunkt”, because it is produced in the Meilo plant. MK352 is the basis for high-calorific mixed plastic waste. The composition of MK352 is the following (% values below referred to mass / weight):

- Consists mainly of PE, PP, PS (typical plastics used for packaging)
- Maximum: 10 % of impurities in sum
- Paper and cardboard < 5 %
- Metals < 2 %
- PET bottles < 3 %
- PVC < 0,5 %
- Others (e.g. glass, stone, wood, textiles, food waste) < 3 %
- LHV: 20-30 MJ/kg

The MK352 has the same composition as the MK350 MPW fraction, although this is available in large quantities in Germany (see CE Delft, 2019), the term MK352 is more often used nowadays.

High-calorific mixed plastic waste

The MPW, represented by MK352, is obtained after the sorting plan. Following extra sorting, high-calorific mixed plastic waste is generated suitable for input to the pyrolysis plant is obtained by removing the 10% of impurities contained in MK352. The main characteristics are the following:

- LHV: 44 MJ/kg
- Consists only of PE, PP, PS (typical plastics used for packaging)

(Residual) municipal waste

The average municipal waste which is removed after the extra sorting of MPW is a mix of glass, stone, wood, few plastics like PET and PVC, food waste etc. The main characteristic is the following:

- LHV: 8,5 MJ/kg (Sphera, 2019)

Purified pyrolysis oil

The purification of pyrolysis oil - which is the main product of the pyrolysis technology - comprises mainly three steps: de-chlorination, hydrogenation and fractionation. The removal of both chlorine and oxygen is the main task of the purification step. The purified pyrolysis oil is suitable as a naphtha substitute once the chlorine and oxygen have been removed. By-product, waste water and direct emissions to fresh water result from the purification process.

2.2.4. Scenario description

Scenario group 1: Technologies considered in the product systems due to system expansion

Scenario group 1 assesses the influence of national energy grid mixes, both for electricity and thermal energy, in terms of time coverage and geographical coverage within case study #1 with a link to European countries besides Germany and a link to “mid-term” future developments (> 20 years from now) on the energy market. It focuses on the recovered energies that are substituted and result in environmental credits in the system. Two extreme scenarios concerning CO_2-eq.

emissions have been defined with energy produced conventionally from base load energy plants. One assesses the GHG impact on the comparative systems if the recovered energies and electricity are substituted with fossil energies and electricity, the other one with renewable (see Table 2-3).

Table 2-3 Case study #1, Scenario group 1 overview: Technologies considered in the product systems due to system expansion

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 1	× Pyrolysis ✓ 100% MSWI ✓ 100% RDF ✓ 30% MSWI - 70% RDF	**Base case**	Baseline 2030	Recovered energies and electricity substitute anticipated future energy and electricity mixes for Germany in 2030 (see tables 2-11 and 2-12).
		Scenario 1	Energy credit, fossil	Recovered electricity substitutes electricity from lignite. Recovered heat substitutes thermal energy from heavy fuel oil (HFO).
		Scenario 2	Energy credit, de-carbonized	Recovered electricity substitutes electricity from hydro power. Recovered heat substitutes thermal energy from renewable resources (biogas and biomass).

Scenario groups 2 & 3: Target feedstock – mixed plastic waste (MPW)

Two scenarios have been calculated regarding the composition of MPW. One regarding the economic value of MPW and the other one regarding its target composition.

In the first scenario, the base case has been modelled with economic values of 228€ per tonne as average for mono-material plastic waste fractions and 0€ as proxy for residual waste fractions. A scenario shall assess the effects from the economic allocation in the sorting plant on the overall results if the economic value of MPW increases from 110€/tonne to 300€/tonne (Table 2-4). The economic value of mono-material plastic waste stays for base case and scenario fix at 228€/t.

Table 2-4 Case study #1, Scenario group 2 overview: Increment of the economic value of the target feedstock - MPW

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 2	✓ Chemical recycling ✓ 100% MSWI ✓ 100% RDF ✓ 30% MSWI - 70% RDF	**Base case**	Baseline 2030	Economic value of in the sorting plant is set to 110€ per tonne MPW.
		Scenario	MPW economic value 300€/t	Economic value of in the sorting plant is set to 300€ per tonne MPW.

The second scenario focusses on the composition of MPW that is considered to be comparable in 2019 and 2030 in Germany. However, a scenario has been modelled that covers two different aspects:

- It considers a different composition in 2030 with an estimated 30% higher content of PET that results in higher extra sorting effort compared to the baseline scenario to achieve the quality requirements for the target feedstock into pyrolysis plant.
- Also, it considers an improved sorting technology that leads to a higher share of mono-material waste fractions and a decreasing quality of MPW fraction. So, the scenario simulates an increasing extra sorting effort after the sorting plant to improve the characteristics of MPW to a high-calorific MPW (Table 2-5). This is an indicative scenario and not based on actual data.

Table 2-5 Case study #1, Scenario group 3 overview: Increment of extra sorting effort

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 3	✓ Chemical recycling ✓ 100% MSWI ✓ 100% RDF ✓ 30% MSWI - 70% RDF	**Base case**	Baseline 2030	Additional effort of +33% electricity consumption of extra sorting after the sorting plant.
		Scenario	Extra sorting effort (+100%)	Additional effort of +100% electricity consumption of extra sorting after the sorting plant.

Scenario groups 4 & 5: Core technologies considered in the product systems

Two scenarios have been analysed regarding core technologies in the product system for pyrolysis: the pyrolysis and the purification processes.

The purification scenario examines the effect on the overall climate change result if the quality and the product characteristics of purified pyrolysis oil does not reach naphtha quality. As estimation, the material substitute is fossil-based heavy vacuum residue (HVR) in this scenario instead of fossil-based naphtha (Table 2-6).

Table 2-6 Case study #1, Scenario group 4 overview: Purification efficiency

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 4	✓ Chemical recycling × 100% MSWI × 100% RDF × 30% MSWI - 70% RDF	**Base case**	Baseline 2030	Purified pyrolysis oil substitutes fossil-based naphtha.
		Scenario	Purification scenario - HVR substitution	Purified pyrolysis oil substitutes fossil-based heavy vacuum residue (HVR).

The pyrolysis scenario examines the effect on the overall climate change result if carbon conversion efficiencies in the pyrolysis process improve in the upcoming years. Carbon conversion efficiency strongly affects the carbon dioxide direct emissions. As estimation, conversion efficiencies of 77% and 87% are evaluated (Table 2-7). A carbon conversion efficiency evaluation lower than 71% is not realistic as 71% is already based on data from a commercial plant. It is more likely that pyrolysis efficiencies are going to increase in the future.

Table 2-7 Case study #1, Scenario group 5 overview: Carbon conversion in pyrolysis process

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 5	✓ Chemical recycling × 100% MSWI × 100% RDF × 30% MSWI - 70% RDF	**Base case**	Baseline 2030	Carbon conversion efficiency of the pyrolysis process is 71%
		Scenario 1	77% efficiency	Carbon conversion efficiency of the pyrolysis process is 77%
		Scenario	87% efficiency	Carbon conversion efficiency of the pyrolysis process is 87%

Scenario group 6: Further technologies as part of the system – Cement kiln

One further technology for the treatment of mixed plastic waste is the cement kiln. This scenario investigates an additional comparative system to add a further aspect to the goal and scope of the case study #1. As such, there is no complementary base case.

Industry average data for Germany for 2017 have been applied (VDZ, 2018) since reliable forecasts for the future fuel mix are not available. However, the electricity consumed in the cement kiln process has been modelled based on the anticipated 2030 German grid mix (Table 2-15). In comparison to many other European countries, the German situation regarding the share of fossil and alternative fuels used in cement kilns is already high developed. The general progress in terms of fuel input is a shift from fossil to alternative fuels (including renewable energy sources). In the past 10 years in Germany, the share of alternative fuels increased from 54% in 2008 to 65% in 2017. Nowadays, MPW is the most important alternative fuel by mass and energy input. It is assumed that the share of alternative fuels will further increase in Germany and in other European countries and that the process efficiency might be further optimised. However, it is difficult to forecast the future emissions profile of cement kilns resulting from adaptations in the fuel input mix and improved efficiency. As such, the default scenario in this study assumes that the 2017 data basis for German cement kilns is also applicable in 2030.

The system boundary and the functional unit for this additional system are the following:

- Functional unit:

  The functional unit is the treatment of 1 tonne of MPW.

- System boundaries:
  Included in the system boundaries are the waste collection and sorting (incl. a split of 90% high calorific MPW and 10% impurities). Impurities are incinerated in an MSWI with energy recovery. High-calorific MPW is considered to be an alternative fuel input in the cement kiln. The “original” cement kiln process data of the dataset (Sphera, 2019) have been adapted. As the cement kiln produces cement clinker, a system expansion approach is performed: clinker with adapted fuel mix substitutes clinker with “original” fuel mix (based on 2017 data of industry average in Germany incl. 2030 German grid mix).

To test the effect on the overall climate change results of possible future changes in the fuel mix in cement kilns with focus on the application of mixed plastic waste, three different scenarios have been

analysed in this scenario group. The prerequisite for all scenarios is that the sum of energy input of fossil and alternative fuels is constant (based on 2017 data of industry average in Germany (VDZ (2018)).

Scenario 6.1: MPW is replaced mainly by a mix of other alternative fuels

Rationale:

Other alternative fuels besides MPW (e.g. waste tyres, waste oil, animal fat, mixed fractions of municipal waste, solvents, sewage sludge, oil sludge, organic distillation residues etc.) are sufficiently available. The application of MPW is shifting from waste-to-energy (incl. usage as fuel cement kiln) towards material and pyrolysis.

Adaptation of cement kiln process:

- *Assumption for adapted fuel input*: 5 kg high-calorific MPW input (LHV: 44 MJ/kg) in cement kiln per tonne of clinker instead of 76 kg MPW (LHV: 20 MJ/kg) per tonne of clinker. This means that about 15% remaining energy input is based on plastic, i.e. 85% of the original energy input due to plastic is replaced by other alternative fuels.
- The mix of other alternative fuels besides MPW has been scaled up to balance the missing energy input of MPW.
- *Assumption for adapted emission profile*: emission profile of alternative fuels is changing as mass input of alternative fuels increases totally by 38% with 26% increase of fossil-based alternative fuels. This leads to a higher amount of fuel input (in terms of mass) with lower LHV in average while the share of renewable alternative fuels increases → fossil CO_2 emissions +5%, biogenic CO_2 emissions +5% compared to the “original” cement kiln emission profile for alternative fuels.
- CO_2 emission profile of fossil fuels and of raw materials remains constant – they account for 85% of total fossil CO_2 emissions of cement kiln.
- Overall the CO_2 emission profile of the cement kiln increases due to the adaptation by 0,8% for fossil CO_2 emissions and 5% for biogenic CO_2 emissions (share of biogenic CO_2 emission of total CO_2 emissions at cement kiln: 7%)

Scenario 6.2: MPW replaces all alternative fuels

Rationale: In this other theoretical scenario the effects on the changing eco-profile of clinker with a 100% high calorific MPW input as alternative fuel are tested. All other alternative fuels are replaced by high-calorific MPW.

Adaptation of cement kiln process:

- *Assumption for adapted fuel input*: 57 kg high-calorific MPW input (LHV: 44 MJ/kg) in cement kiln per tonne of clinker. No other alternative fuels have been used. Raw material input and input of fossil fuels remain constant.
- *Assumption for adapted emission profile*: emission profile for alternative fuels is adapted → fossil CO_2 emissions +50 kg CO_2 per tonne clinker, biogenic CO_2 emissions -60 kg CO_2 per ton.
- Overall the CO2 emission profile of the cement kiln increases due to the adaptation by 6,5% for fossil CO_2 emissions. No biogenic CO_2 emissions after adaptation have been released.

Scenario 6.3: MPW replaces lignite

Rationale: In this scenario an increasing share of alternative fuels has been examined. Lignite is the most widely used fossil fuel with about 60% share at energy input of fossil fuels in cement kiln. Therefore, it is assumed that lignite is replaced by MPW. All other alternative fuels remain constant.

Adaptation of cement kiln process:

- *Assumption for adapted fuel input*: 57 kg high-calorific MPW input (LHV: 44 MJ/kg) in cement kiln per tonne of clinker. Amount of lignite input is reduced accordingly (sum of energy input of fossil and alternative fuels is constant). All other alternative fuels remain constant (130 kg alternative fuel input per tonne of clinker). Raw material input remains constant.
- *Assumption for adapted emission profile*: emission profiles of lignite combustion and high-calorific MPW combustion from GaBi database are applied to calculate the resulting new emissions for CO_2, CO, SO_2, NMVOC and NO_x according to adapted lignite and MPW mass inputs into cement kiln.
- Changes after adaptation compared to “original” cement kiln emission profile (emissions due to additional MPW input minus avoided emissions due to reduced lignite input):
    - CO_2: -4%
    - CO: -1%
    - SO_2: -39%
    - NMVOC: +1%
    - NO_x: -10%

2.2.5. Time Coverage

The intended time reference is the year 2030. All elements in the assessed baseline systems have been adapted to the best extent possible to this time reference as described in section 2.2.2.

2.2.6. Technology Coverage

The intended technology references cover the end of life options for MPW in Germany in the year 2030:

- Waste-to-energy (MSWI and RDF)
- Pyrolysis and purification
- Cement kilns.

Further technologies are covered in case study #1 that are linked to these core technologies:

- Generation of electricity and thermal energy in 2030 based on 100% fossil resources
- Generation of electricity and thermal energy in 2030 based on 100% renewable energy resources
- Sorting plant of mixed waste collected from household (including mainly lightweight packaging wastes)
- Extra sorting of mixed plastic waste to generate high-calorific mixed plastic waste (feedstock for pyrolysis technology)

2.2.7. Geographical Coverage

The intended geographical reference is Germany.

The scenario analyses extend the geographical coverage to other European countries besides Germany.

2.2.8. Allocation

Multi-output allocation

Multi-output allocation generally follows the requirements of ISO 14044, section 4.3.4.2. Where allocation is necessary, the allocation rule most suitable for the respective process step has been applied and is documented below.

Economic allocation applied in sorting plant

Three waste fractions are considered with the respective amounts of recovered waste: mono-material plastic waste fraction, mixed plastic waste fraction and residual waste fractions. Data have been sourced from a recent LCA study of the Meilo sorting plant (Kaitinnis, 2019). Prices for the waste fractions obtained after the sorting process have been taken from (EUWID, 2019) and Dr Andreas Kicherer (BASF, Technical information from BASF experts, 2019) and adapted to the expected values in 2030.

    - Mono-material plastic waste: 228 Euro per ton
    - MPW fraction: 110 Euro per ton
    - Residual waste fractions: 0 Euro per ton
- Effect of economic allocation: due to the application of the economic allocation, about 19,5% of environmental loads of sorting plant are allocated to target feedstock MPW
    - Mono-material plastic waste: 68,4 Euro per tonne of waste sorted
    - MPW fraction: 16,5 Euro per tonne of waste sorted
    - Residual waste fractions: 0 Euro per tonne of waste sorted

System expansion in pyrolysis process

- Pyrolysis oil as main product and char as by-product.
- Characteristics of char: 85% carbon content, 20 MJ/kg.

- Char is used as a fuel in applications such as cement kilns. Due to having similar LHV and applicability to lignite, this is used as material substitute. (BASF, Technical information from BASF experts, 2019). Another possible application for char would be road construction, so a material substitute for gravel. The effect on the overall results is very limited (below 3%). As the effect on the overall results is small and the application of char in cement kilns is more likely, the cement kiln options is applied.

Allocation of background data (energy and materials) taken from the GaBi 2019 databases is documented online at http://gabi-software.com/support/gabi/gabi-database-2019-lci-documentation/.

End-of-Life (EoL) allocation

End-of-Life allocation generally follows the requirements of ISO 14044, section 4.3.4.3.

Material substitution (or "avoided burden" approach): the mass of recovered secondary material is used to scale the substituted primary material, i.e., applying a credit for the substitution of primary material so as to distribute credits/burdens appropriately among the different product life cycles. These subsequent process steps are modelled using industry average inventories.

- Purified pyrolysis oil substitutes fossil-based naphtha – substitution factor is assumed to be 1:1. Justification is provided in sections 2.2.2 and 2.2.3

Energy recovery & substitution (or "avoided burden" approach): In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are assigned for power and heat outputs.

- Recovered electricity from MSWI substitutes electricity from German grid mix in 2030.
- Recovered thermal energy from MSWI substitutes thermal energy generated in Germany in 2030.

2.2.9. Cut-off Criteria

No cut-off criteria have been defined for this study. As summarized in section 0, the system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The influence of these proxy data on the results of the assessment is discussed in Chapter 5.

2.2.10. Selection of LCIA Methodology and Impact Categories

This study assesses LCIA results based on two different sets of indicators:

- *Environmental Footprint (EF) 2.0* (European Commission, EF 2.0 reference package, June 2018 - https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml, 2018)
- *ReCiPe 2016, v1.1* (RIVM et al, 2016) – Hierarchical (H) midpoint indicators

The results of all indicators on midpoint level are shown in Annex A. As core sets of indicators for this study, the EF 2.0 indicators have been selected since this European framework has gained broad attention from industry and academia due to its potential application in future European regulations, it was deemed as an appropriate basic set of impacts to evaluate for a study whose main audience

is expected in the European market. The ReCiPe indicators were selected to check and discuss possible differences for single indicators due to different methodologies applied.

Table 2-8: Set of recommended impact methods in EF 2.0

Method	Description
Acidification terrestrial and freshwater	Accumulated Exceedance (AE). Change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems.
Cancer human health effects	Comparative Toxic Unit for human (CTUh). Estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme).
Climate Change	Global Warming Potential 100 years, based on IPCC AR5 including climate carbon feedback
Climate Change (biogenic)	These are subsets of the total Climate Change covering the biogenic, fossil, and land use related part of the climate change. These three add up to the main climate change impact.
Climate Change (fossil)	
Climate Change (land use change)	
Ecotoxicity freshwater	Comparative Toxic Unit for ecosystems (CTUe). The potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 year/kg).
Eutrophication freshwater	Phosphorus equivalents: The degree to which the emitted nutrients reach the freshwater end compartment (phosphorus considered as limiting factor in freshwater).
Eutrophication marine	Nitrogen equivalents: The degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water).
Eutrophication terrestrial	Accumulated Exceedance (AE). The change in critical load exceedance of the sensitive area.
Ionising radiation - human health	Ionizing Radiation Potentials: The impact of ionizing radiation on the population, in comparison to Uranium 235.
Land Use	Soil quality index based on the LANCA methodology
Non-cancer human health effects	Comparative Toxic Unit for human (CTUh). The estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme).
Ozone depletion	Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.
Photochemical ozone formation - human health	Expression of the potential contribution to photochemical ozone formation. Tropospheric ozone concentration increases as NOx equivalents.
Resource use, energy carriers	Abiotic resource depletion fossil fuels (ADP-fossil)
Resource use, mineral and metals	Abiotic resource depletion (ADP ultimate reserve).

Respiratory inorganics	Deaths due to kg of PM2.5 emitted. The unit is changed into 'Disease incidents' rather than 'Deaths'. However, the change happened after the beginning of the February 2018 update procedure and the change is not implemented until later in 2018
Water scarcity	m3 water eq. deprived

BASF has developed an own method for human toxicity assessments, see (Landsiedel & Saling, 2002). This toxicity indicator is assessed in addition to the existing toxicity indicators in EF 2.0 and ReCiPe.

The analysis, discussion and interpretation of the study results is focussing on selected relevant indicators:

- Climate change
- Acidification
- Eutrophication, freshwater and marine
- Photochemical ozone formation, human health
- Resource use, energy carriers
- Human toxicity (BASF method)

Justification for the selection of relevant LCA indicators:

- Climate change is of high public and institutional interest and deemed to be the most pressing environmental issue of our time.
- Photochemical ozone formation, eutrophication and acidification were chosen because they are closely connected to air and water quality and capture the environmental burdens associated with commonly regulated emissions such as NOx and SO2.
- Depletion of energy resources was chosen in order to show how the systems depend on the respective fossil-based feedstocks.
- Toxicity according to independent methods like USEtox were not determined, because of the lack of appropriate data for BASF processes. Thus, the BASF human toxicity method developed by Landsiedel & Saling was chosen.
- Ozone depletion potential is not considered in this study as no ozone-depleting substances are emitted in the foreground system. Moreover, as a result of the Montreal Protocol, most CFCs have already been phased out and HCFCs will be by 2030.
- Further impact categories recommended in the EF 2.0 set of indicators were not considered. The list includes ecotoxicity (large uncertainty), ionising radiation, resource use of minerals and metals (not internationally accepted), water scarcity and respiratory inorganics (relevant information for assessing these impact categories according to goal and scope of the study is lacking in most of the used background datasets).

A description of selected impact categories is provided in Annex D: . The focus lies on the Environmental Footprint framework as selected set of indicators. Remarks on the ReCiPe methods have been included in cases where there are differences to EF 2.0.

2.2.11. Interpretation to Be Used

The results of the LCI and LCIA are interpreted according to the Goal and Scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results

- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations and recommendations

Note that in situations where no system outperforms all of its alternatives in each of the impact categories, some form of cross-category evaluation is necessary to draw conclusions regarding the environmental superiority of one system over the other. Since ISO 14044 rules out the use of quantitative weighting factors in comparative assertions to be disclosed to the public, this evaluation will take place qualitatively and the defensibility of the results therefore depend on the authors' expertise and ability to convey the underlying line of reasoning that leads to the conclusion.

2.2.12. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using either
    - measured or calculated primary data or
    - secondary data based on industry-average data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results. This ability is limited by the exclusion of confidential primary data (however, available for review panel in confidential Annex C:) and access to the same background data sources.
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope. The goal is to use the most representative data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g., no industry-average data available for a certain country), best-available proxy data were employed.

An evaluation of the data quality with regard to these requirements is provided in Chapter 5 of this report.

2.2.13. Type and format of the report

In accordance with the ISO requirements (ISO 14044, 2006) this document aims to report the results and conclusions of the LCA completely, accurately and without bias to the intended audience. The results, data, methods, assumptions and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.2.14. Software and Database

The LCA model was created using the GaBi 9 Software system for life cycle engineering, developed by Sphera. The GaBi 2019 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

2.2.15. Critical Review

A panel review according to ISO 14044, section 6.3 has been undertaken. The review has been conducted in accordance with ISO/TS 14071:2014 (ISO/TS 14071, 2014).

Names and affiliations of reviewers

- Chair of panel Prof. Adisa Azapagic, Ethos Research
- Co-reviewer Simon Hann, Eunomia Research & Consulting Ltd.
- Co-reviewer Dr Florian Antony, Öko-Institut e.V. (Institute for Applied Ecology)

The Critical Review Statement can be found in Annex B. The Critical Review Report containing the comments and recommendations by the independent experts as well as the practitioner's responses is available upon request from the study commissioner in accordance with ISO/TS 14071.

2.3. Life Cycle Inventory Analysis

2.3.1. Data Collection Procedure

Primary data were collected using customised data collection templates, which were sent out by email to the respective data providers in the participating companies. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. If gaps, outliers, or other inconsistencies occurred, Sphera engaged with the data provider to resolve any open issues.

Secondary data were collected from a variety of different literature sources. Each data source was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. Sources used in the model are given throughout the report document.

Secondary data from GaBi was used in the foreground system of the model, GaBi databases uses are given throughout the report document. Documentation for all GaBi datasets can be found online (Sphera, 2019).

2.3.2. Foreground System

Mixed waste collection

Mixed waste from yellow bags is collected at the point of generation (households), transported to the collection plant and then to the sorting plant by truck. After sorting, the MPW fraction is finally sent to the waste treatment plant. Transportation distances are given in Table 2-9 [Source: (Kaitinnis, 2019) and (BASF, Technical information from BASF experts, 2019)].

In the foreground system, secondary data from the GaBi databases for transportation vehicles and fuels are used. These databases are representative for vehicle types, sizes and technologies. A

diesel-driven Euro 6 truck with a capacity of 28t is used. Empty return load during collection and transportation of mixed waste is also considered.

Table 2-9 Transport distances

Waste	Transport process	Distance [km]	DQI
Mixed waste	Point of generation to collection plant	30	Literature
Mixed waste	Collection plant to sorting plant	80	Estimated by expert
MPW	Sorting plant to waste treatment plant	50	Estimated by expert

Mixed waste sorting

Mixed waste is sorted into different fractions based on secondary data from the Meilo plant. 13 different waste fractions are reported but, to reduce complexity and to enable the use of economic allocation, those waste fractions are combined into 3 main waste groups: Mixed plastic waste, mono-material plastic waste (PE, PP, PS, PET) and further waste fractions (tinplate, aluminium, paper & cardboard, beverage cartons, and residual mixed waste fractions). The Meilo sorting process consists of 12 steps, to separate the valuable waste fractions and to remove different kind of impurities. The total electricity consumption and the fractions are given in Table 2-10 [Source: (Kaitinnis, 2019)].

Table 2-10 Unit process sorting of mixed waste

Type	Flow	Value	Unit	DQI
Inputs	Electricity	0,19	GJ	Measured
	Mixed waste	1,00	t	Measured
Outputs	MPW fraction	0,15	t	Measured
	Mono-material plastic waste	0,30	t	Measured
	Residual waste fractions	0,55	t	Measured

The target waste fraction for the pyrolysis process is the MPW fraction. Economic allocation is used to distribute the environmental burdens of the other waste fractions as described in chapter 2.2.8. Prices for the waste fractions obtained after the sorting process are given in Table 2-11 Source (EUWID, 2019) and Dr, Andreas Kicherer (BASF, Technical information from BASF experts, 2019).

Table 2-11 Prices of waste fractions

Waste fraction	Price [€/t]	DQI
MPW fraction	110	Estimated by expert
Mono-material plastic waste	228	Literature
Residual waste fractions	0	Estimated by expert

In the foreground system, secondary data from the GaBi databases for fuels are used, these databases are representative of the geographies and technologies used

MPW extra sorting

Mixed plastic waste is transported 50 km (Dr Andreas Kicherer (BASF, Technical information from BASF experts, 2019))) to the pyrolysis plant, RDF plant or cement plant for further processing. It is assumed that the final treatment of high caloric value MPW takes place in Germany.

Secondary data from the GaBi database are used to model transportation vehicles and fuels. These databases are representative for vehicle types, sizes and technologies. A diesel-driven Euro 6 truck with a capacity of 28t is used, empty return load has also been modelled.

The MPW is extra sorted to improve certain technical characteristics (e.g. calorific value) in such a way that the waste can be used as feedstock in the further processes. The total electricity consumption and the waste fractions obtained by the extra sorting are given in Table 2-12. In the foreground system, secondary data from the GaBi databases for fuels are used, these databases are representative of the geographies and technologies used.

The impurities resulting from the extra sorting are transported and treated in a municipal solid waste incineration plant with energy recovery. A diesel-driven Euro 6 truck with a capacity of 28t is used to transport the impurities by 50km (Dr Andreas Kicherer (BASF, Technical information from BASF experts, 2019)). The empty return transport during collection and transportation of mixed waste has been modelled. Secondary data from the GaBi databases for transportation vehicles and fuels have been used, these databases are representative for vehicle types, sizes and technologies.

Table 2-12 Unit process extra sorting of MPW

Type	Flow	Value	Unit	DQI
Inputs	Electricity	58	MJ	Derived from measured data
	MPW	1,0	T	Derived from measured data
Outputs	High calorific MPW	0,9	T	Based on MK352 composition
	Impurities	0,1	T	Based on MK352 composition

Pyrolysis and purification steps

Pyrolysis is the thermal decomposition of materials at elevated temperatures in an inert atmosphere. It is a thermochemical treatment process that can be applied to any organic (carbon-based) product. Thus, it is a process of controlled cracking of long hydrocarbon chains, that can be likened to the activity of a refinery where, instead of crude oil, the input is plastic waste. The pyrolysis step is a “reverse” process to the refinery - the plastic is brought back into its "initial" liquid components by using heat in the absence of oxygen.

In the pyrolysis step, the high-calorific mixed plastic waste is heated in the absence of oxygen until it melts, and the polymer molecules break down to form a rich saturated hydrocarbon vapor. The condensable gases are converted to pyrolysis oil by atmospheric distillation. The non-condensable gases are collected separately and combusted to generate energy.

Primary data from industry at commercial plant level has been used in the model, the unit process information including conversion efficiency to purified pyrolysis oil is provided in Annex C. Pyrolysis oil and char are the resulting products from the pyrolysis process.

The by-product char is treated with the system expansion approach as described in section 2.2.8. Due to the calorific value of the char, this by-product is commonly used as alternative fuel in cement kilns where it replaces lignite as the most widely applied fossil fuel. Secondary data from the GaBi database for “lignite mix production” in Germany has been used for the system expansion

(material/fuel substitution) considering the equivalent energy content based on LHV as the substitution factor.

In this study additional process steps were estimated to transfer the commercial pyrolysis technology from a commercial manufacturer to Germany running with mixed plastic waste from the German yellow bag:

- Sorting of German yellow bag and extra sorting of high calorific mixed plastic fraction in order to fulfil the pyrolysis feedstock specification. : Three main steps are conducted in the purification process: dechlorination, hydrogenation to remove the oxygen and fractionation as a separation step. Primary data from industry at laboratory scale is used to model these processes.. Pyrolysis oil is transported to the purification plant 500 km (estimated by Dr Stefan Strege, BASF) by an electric average train. The by-product heavy vacuum residue resulting from the purification step is treated with the system expansion approach as described in section 2.2.8. Due to its calorific value, this by-product can be used as alternative fuel or for material production.

In the foreground system, the GaBi databases for fuels and auxiliaries are used, these databases are representative of the geographies and technologies used.

Municipal Solid Waste Incineration

In the foreground system, secondary data from the GaBi database for municipal solid waste incineration of plastic packaging waste has been used. The thermal treatment of a single waste fraction like plastic packaging waste is not done in a waste to energy plant, instead, a wide range of different waste streams are treated together. However, the database settings for the average MSW dataset allows the model to attribute the environmental burdens, energy production and credits to a single fraction or specific waste within an average MSW mix. In the database, the waste fraction is homogenized to obtain a relatively constant calorific value and to align with the emission regulation.

The MSWI dataset represents the thermal treatment of plastic packaging waste with a net calorific value of 36 MJ/kg. To make the MSWI dataset comparable with the pyrolysis of MPW (with a net calorific value of 44 MJ/kg), the environmental impacts and the auxiliaries used in the incineration process as well as the credits associated with the energy generated have been manually increased by 22..This as a good approximation with focus on energy, carbon content and climate change and a fair approximation for all other environmental indicators.

Produced steam is used internally as process-steam and the surplus is used to generate electricity or exported. The energy consumption for the plant was modelled specific to Germany using data from ITAD (German association for waste-to-energy plants), which represents 69 German waste-to energy plants in 2008. The energy consumption for the average combusted waste was extrapolated to the heat input of the specific waste and the waste specific differences on the own consumption of energy (steam and waste) and auxiliaries. The MSWI process has been modelled as a multi-output process, the surplus electricity and steam resulting of the thermal treatment have been accounted for as by-products. The net energy efficiency is 44,6%, 11,3% is electricity and 33,3% is steam (Umweltbundesamt, Umweltbundesamt auf Basis Arbeitsgemeinschaft Energiebilanzen: Energiedaten, Stand Dezember 2018, 2018)

The plant consists of an incineration line fitted with a grate and a steam generator, the dataset also covers all relevant process steps for the thermal treatment and the disposal of air pollution residues and metal recycling. The database is partly terminated, electricity and steam resulting of the thermal treatment are open.

A dry technology with adsorbent and a selective catalytic reduction (SCR) system for NO_x-reduction have been modelled for the flue gas treatment. Ammonia is used as a reducing agent and is directly injected into the furnace to react with the NO_x, resulting into nitrogen and water. Adsorbent agents are added to the flue gas, which is finally passed through fabric filters. Lime milk and small parts of hearth furnace coke are used as adsorbents; part of the adsorbent agents is re-circulated. The fly ash, together with the adsorbent, are mixed together with the boiler ash.

For the emissions HCl, HF, NO_x, VOC, N_2O, CO, NH_3, SO_2, dust, dioxin and the heavy metals As, Cd, Co, Cr, Ni and Pb mean emission values per cubic meter of cleaned flue gas published in the BREF document "Waste Incineration" of the European Commission have been used. Due to the wide range of emissions for some elements and substances, the mathematical mean values have been adjusted with additional real plant data. The emission of all other elements and the distribution of all elements and substances into the different residues were based on calculated values.

Documentation for all GaBi datasets can be found online.

Refuse Derived Fuel

In the foreground system, secondary data from the GaBi database for municipal solid waste incineration of plastic packaging waste have been used as estimation. Based on expert knowledge (Dr. Karl Hölemann, BASF), the technology for the MSWI and RDF plants is considered to be comparable. Only for RDF plants the MPW is extra-sorted to guarantee the technical characteristics (e.g. calorific value) of the feedstock.

The municipal solid waste incineration has been modelled as a multi-output process, the surplus electricity and steam resulting of the thermal treatment are accounted for as by-products. The net energy efficiency is 52%, 15% is electricity and 37% is steam (Umweltbundesamt, Energieerzeugung aus Abfällen – Stand und Potenziale in Deutschland bis 2030, Texte /2018, Juni 2018, 2018).

Cement clinker production

In the foreground system, secondary data from the GaBi database for cement clinker has been used. The model was developed based on the report (VDZ, 2018). The environmental data were based on the records of the emissions monitoring and single measures of trace elements and organic exhaust gas compounds in the German cement plants.

Cement clinker kilning is the step that uses almost all the energy consumed in the cement manufacturing. While traditional fossil fuels may be used in the clinker kilning step, the use of alternative fuels is widespread. In Germany 64% of the total energy consumption of the cement clinker is obtained from the alternative fuels. (VDZ, 2018). In the model, the composition of the fossil and alternative fuels is taken from VDZ (2018), direct emissions from the cement clinker are linked to the composition of the fuels. The fuel composition is given in

Table 2-13.

Table 2-13 Fuel mix used in cement clinker kiln

Fuel	Share [%]
Coal	9,0
Lignite	20,8
Petcoke	3,7
Heavy fuel oil	0,4
Fuel oil	0,8
Natural gas and other gases	0,5
Other fossil fuels	0,3
Alternative fuels	64,4

The composition of the alternative fuels is given in Table 2-14. In the GaBi database the industrial and commercial waste fraction “others” is modelled as industrial and commercial waste plastics.

Table 2-14 Alternative fuels composition for the cement clinker kiln

Fuel	1000t/a
Waste tyres	221
Waste oil	24
Industrial and commercial waste	
- Pulp, paper and cardboard	93
- Plastics	654
- Others	1127
Meat, bone meal and animal fat	149
Mixed fractions of municipal waste	317
Solvents	145
Sewage sludge	382
Others	65

In Germany, the total average energy consumption per tonne of cement is 2,869 MJ for fuel energy and 111,2 kWh electrical energy. Fuel energy is primarily required for clinker burning, while electrical energy is use for the raw material pre-treatment, burning and cooling of the clinker and cement grinding (VDZ, 2018).

2.3.3. Background System

Documentation for all GaBi datasets can be found online (Sphera, 2019).

Fuels and Energy

Electricity mix and thermal energy reflects the energy-related objectives that the international community has set with the United Nations 2030 Agenda for Sustainable Development, with a significant reduction the carbon intensive fossil fuels and a proportional increase of renewable fuels. The electricity fuel mix are presented in Table 2-15. The thermal energy fuel mix are presented in Table 2-16 (ExxonMobil, 2018).

Table 2-15 German electricity mix 2030

Fuel type	Electricity mix [%]	DQI
Electricity from biogas	4,4	Literature
Electricity from biomass (solid)	2,4	Literature
Electricity from coal gases	1,6	Literature
Electricity from geothermal	0,2	Literature
Electricity from hard coal	7,4	Estimated by expert
Electricity from heavy fuel oil (HFO)	0,5	Literature
Electricity from hydro power	3,9	Literature
Electricity from lignite	8,1	Estimated by expert
Electricity from natural gas	16,2	Literature
Electricity from nuclear	0,0	Literature
Electricity from photovoltaic	21,1	Estimated by expert
Electricity from waste	2,0	Literature
Electricity from wind power	32,2	Estimated by expert

The electricity mix consider the electricity supply for final consumers, including electricity own consumption, transmission/distribution losses of low voltage electricity supply and electricity imports from neighbouring countries.

Table 2-16 German thermal energy mix 2030

Fuel type	Thermal energy mix [%]	DQI
Thermal energy from biogas	18,0	Calculated
Thermal energy from biomass (solid)	18,0	Calculated
Thermal energy from light fuel oil (LFO)	13,0	Calculated
Thermal energy from natural gas	51,0	Calculated

German databases for fuels, electricity and energy from GaBi are used in the model. The key energy datasets used in the foreground system are presented in Table 2-17. Electricity produced internally within the BASF facilities is considered in the model.

Table 2-17: Key energy datasets used in inventory analysis

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Electricity	DE	Electricity from biogas	Sphera	2018	no
Electricity	DE	Electricity from biomass (solid)	Sphera	2018	no
Electricity	DE	Electricity from coal gases	Sphera	2018	no
Electricity	DE	Electricity from geothermal	Sphera	2018	no
Electricity	DE	Electricity from hard coal	Sphera	2018	no
Electricity	DE	Electricity from heavy fuel oil (HFO)	Sphera	2018	no
Electricity	DE	Electricity from hydro power	Sphera	2018	no
Electricity	DE	Electricity from lignite	Sphera	2018	no
Electricity	DE	Electricity from natural gas	Sphera	2018	no
Electricity	DE	Electricity from photovoltaic	Sphera	2018	no
Electricity	DE	Electricity from waste	Sphera	2018	no
Electricity	DE	Electricity from wind power	Sphera	2018	no
Electricity	BASF	Electricity production mix	BASF	2018	no
Thermal energy	DE	Thermal energy from biogas	Sphera	2018	no
Thermal energy	DE	Thermal energy from biomass (solid)	Sphera	2018	no
Thermal energy	DE	Thermal energy from light fuel oil	Sphera	2018	no
Thermal energy	DE	Thermal energy from natural gas	Sphera	2018	no
Natural gas	DE	Natural gas	Sphera	2018	no

Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2018 database. Table 2-18 shows the most relevant LCI datasets used in modelling the product systems.

Table 2-18: Key material and process datasets used in inventory analysis – case #1

Location	Dataset	Data Provider	Reference Year	Proxy?
DE	Waste incineration (municipal waste)	Sphera	2018	no
DE	Nitrogen allocated by volume	BASF	2018	no
DE	Compressed air	BASF	2018	no
DE	Hydrogen 25 bar	BASF	2018	no
DE	Sodium methylate, 30% solution in Methanol	BASF	2018	no
DE	Tap water from groundwater	Sphera	2018	no
DE	Demineralized Water LU (Water 0% consumptive)	BASF	2018	no
DE	Municipal wastewater treatment (mix)	Sphera	2018	no
DE	Lignite mix	Sphera	2016	no
DE	Naphtha at refinery	Sphera	2016	no
DE	Heavy Vacuum Residue	Sphera	2019	no

Transportation

Transportation in different stages of the system are model using the GaBi global transportation databases. Fuels are model using the geographically appropriate databases.

Table 2-19: Transportation and fuel databases

Location	Dataset	Data Provider	Reference Year	Proxy?
GLO	Rail transport cargo - Electric, average train, gross tonne weight 1,000t / 726t payload capacity	Sphera	2018	yes
GLO	Truck-trailer, Euro 6, up to 28t gross weight / 12.4t payload capacity	Sphera	2018	yes
DE	Diesel mix at filling station	Sphera	2016	no

2.3.4. Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the "outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment". The table below displays a selection of flows based on their relevance in terms of contribution (>99%) to the subsequent impact assessment categories, please see section 2.2.10.

Table 2-20 LCI results of case study # 1*

Flow	Unit	Pyrolysis	100% MSWI	100% RDF	30% MSWI, 70% RDF
Resources					
Carbon dioxide**	kg	46,1	-861,9	-987,8	-950,0
Energy resources					
Crude oil (in MJ)	MJ	-28.399,6	-1.981,5	-2.272,9	-2.185,5
Hard coal (in MJ)	MJ	490,1	-954,9	-1.343,7	-1.227,0
Lignite (in MJ)	MJ	-298,9	-723,8	-1.062,6	-961,0
Natural gas (in MJ)	MJ	1.612,2	-9.524,9	-10.916,4	-10.498,9
Uranium natural (in MJ)	MJ	-35,3	68,6	47,6	53,9
Emissions					
Inorganic emissions to air					
Ammonia	g	7,8	-16,8	-32,2	-27,6
Carbon dioxide	kg	805,3	2.010,0	1.829,4	1.883,6
Carbon dioxide (biotic)	kg	8,4	-906,6	-1.031,9	-994,3
Carbon dioxide (land use change)	kg	-0,1	-9,8	-11,2	-10,8
Carbon monoxide	g	-75,8	-890,6	-1.081,4	-1.024,1

Flow	Unit	Pyrolysis	100% MSWI	100% RDF	30% MSWI, 70% RDF
Nitrogen dioxide	g	2,7	0,5	0,1	0,2
Nitrogen monoxide	g	8,6	-36,2	-43,4	-41,2
Nitrogen oxides	g	-141,6	-1.352,2	-1.622,7	-1.541,6
Nitrous oxide (laughing gas)	g	1,3	-96,1	-110,8	-106,4
Sulphur dioxide	kg	-0,4	-0,7	-0,9	-0,8
Organic emissions to air (group VOC)					
Butane (n-butane)	g	-50,1	-17,8	-20,3	-19,6
Ethane	kg	-0,1	0,0	-0,1	-0,1
Formaldehyde (methanal)	g	0,0	-11,5	-13,1	-12,6
NMVOC (unspecified)	g	-99,2	-63,6	-78,9	-74,3
Pentane (n-pentane)	g	-16,9	-19,1	-21,8	-21,0
Propane	kg	-0,2	0,0	0,0	0,0
Methane	kg	-1,8	-0,6	-0,9	-0,8
Methane (biotic)	kg	0,0	-0,9	-1,0	-1,0
VOC (unspecified)	g	0,1	0,0	0,0	0,0
Inorganic emissions to fresh water					
Ammonia	g	0,0	0,0	0,0	0,0
Chloride	kg	-70,8	-6,2	-7,4	-7,0
Nitrate	g	4,4	-907,5	-1.031,2	-994,1
Nitrogen	g	-0,1	-1,3	-1,4	-1,4
Nitrogen (as total N)	g	1,7	0,0	0,0	0,0
Phosphate	g	-1,8	-46,5	-52,8	-50,9
Phosphorus	g	0,7	-3,3	-3,8	-3,6
Inorganic emissions to sea water					
Chloride	kg	-20,8	-1,5	-1,7	-1,6

* Negative values are due to the system expansion approach for the multioutput processes, see 2.2.8
** Carbon dioxide (resource) has not been corrected in the LCIs of production systems, because mainly waste streams without any biogenic carbon were considered.

2.4. LCIA Results

This chapter contains the results for the impact categories defined in section 2.2.10. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.4.1. Overall Results

The results in the graphs have been broken down to show the contribution to the total impacts from activities in both systems (“process emissions” or “process resource demand”), such as sorting, transportation, incineration, pyrolysis and purification steps and the credits associated with energy and material substitutions (“material/energy substitution”).

Whenever the term “significantly” is used, it refers to minimum differences in results of ±10%.

Climate Change

The overall results for climate change show that the pyrolysis option has significant advantages compared to the incineration options in terms of CO_2-equivalents per functional unit (1 tonne of MPW to be treated).The pyrolysis option results are at least 57% better than the incineration options.

The process emissions of the incineration activities are three times higher than those of the pyrolysis system. However, the credits related to incineration (MSWI and RDF) are also around three times higher compared to pyrolysis. However, as the credits due to material and energy substitution are around 30% of the overall burdens in all systems, the total results are determined by the process emissions. Process emissions are related to the foreground and background activities in the incineration and pyrolysis technologies and activities in the preparation of the MPW.

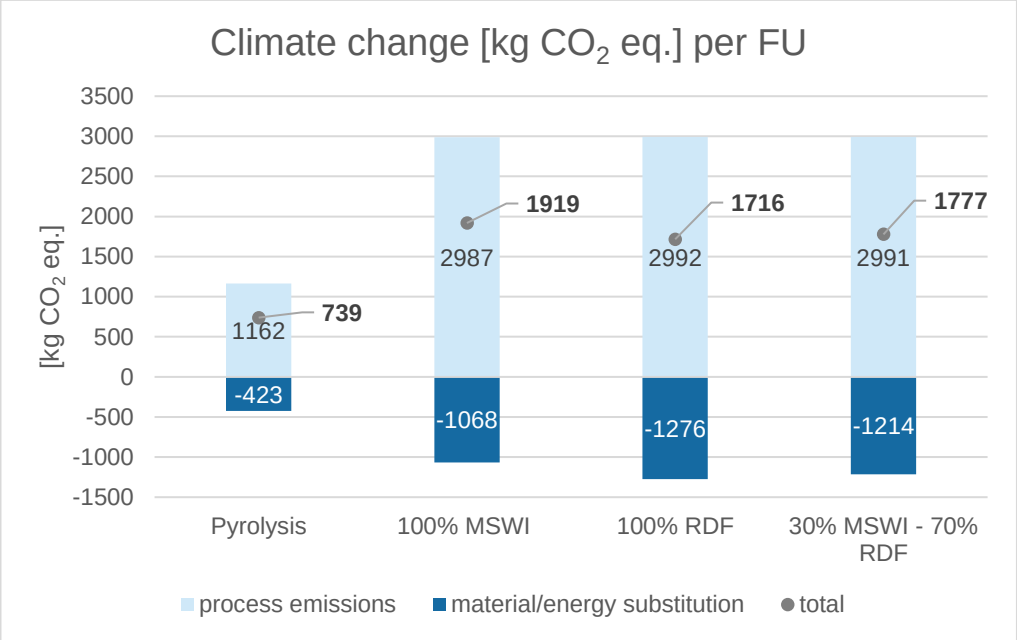


Figure 2-3 EF 2.0 Climate Change total [kg CO2 eq.] per FU – case study #1

Analysis:

The climate change impact are driven by inorganic emissions to air, primarily carbon dioxide.

The figure above shows that the process emission is the dominant contributor to climate change for all technologies under evaluation. For pyrolysis technology, the process emissions is 1162 kg CO_2-eq. Contribution analysis shows that 66% of the impact comes from the pyrolysis oil process, due to the direct emissions, 9% from the impact is from the pyrolysis oil purification process and 26% of the impact is associated to the waste collection, sorting, extra-sorting and transportation. For the incineration technologies (MSWI and RDF), the process emissions are around 2990 kg CO_2-eq. Contribution analysis shows that 93% of the impact comes from the incineration process and 7% of the impact is associated to the waste collection, sorting, extra-sorting and transportation.

Material substitution in the pyrolysis technology is associated with naphtha credits. Energy substitution in the incineration technologies is due to energy credits, contribution analysis shows that around 40% of the impact comes from the electricity credits and 60% from the thermal energy credits (30% MSWI and 70% RDF).

Electricity credits are dominated by the electricity from lignite and electricity from natural gas, which represent about 55% of the total electricity credits. Thermal energy credits are dominated by the thermal energy from natural gas, which represents about 66% of the total thermal energy credits.

Acidification terrestrial and freshwater

The overall results for acidification show that the incineration technologies have significant advantages compared to the pyrolysis technology in terms of Mole of H^+-equivalents per functional unit (1 tonne of MPW to be treated). All options show net-negative impacts.

Credits due to material and energy substitution in the systems under evaluation are relatively high compared to the process emissions related to various activities in the pyrolysis and incineration systems. The burdens are on the same level in the different systems, but the credits are around twice as high in the incineration systems compared to pyrolysis.

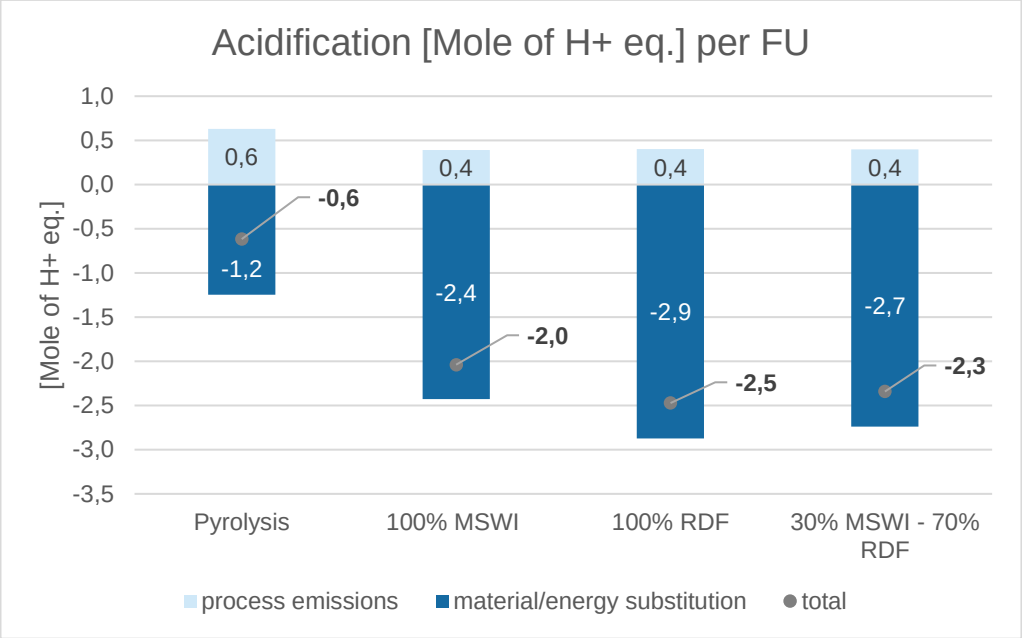


Figure 2-4 EF 2.0 Acidification terrestrial and freshwater [Mole of H^+ eq.] per FU – case study #1

Analysis:

Acidification terrestrial and freshwater is driven by inorganic emissions to air, primarily SO_2 and NO_x emissions

The figure above shows that material and energy substitution is the dominant contributor to acidification terrestrial and freshwater for all technologies under evaluation. Impacts in material substitution for the pyrolysis technology is due to naphtha credits. Impacts in energy substitution for the incineration technologies is due to electricity and thermal energy credits., A contribution analysis shows that around 23% of the impact comes from the electricity credits and 77% from the thermal energy credits (30% MSWI and 70% RDF).

Electricity credits are dominated by the electricity from biogas, from hard coal and for lignite which represent about 59% of the total electricity credits. Thermal energy credits are dominated by thermal energy from biogas and biomass, which represents about 60% of the total thermal energy credits.

For pyrolysis technology, the process emissions are 0,6 Mole of H^+ eq. Contribution analysis shows that 62% of the impact is coming from the pyrolysis oil process, 20% from the pyrolysis oil purification process and 19% is associated to the waste collection, sorting, extra-sorting and transportation. For the incineration technologies (MSWI and RDF) the process emissions are 0,4 Mole of H^+ eq. Contribution analysis shows that 88% of this impact is coming from the incineration process and 12% is associated to the waste collection, sorting, extra-sorting and transportation.

Resource use of energy carriers

The overall result for resource use of energy carriers shows that the pyrolysis option has significant advantages compared to the incineration option in terms of GJ per functional unit (1 tonne of MPW to be treated). All options show net-negative impacts.

The credits due to material and energy substitution in the systems under evaluation are relatively high compared to the process emission related to various activities in the pyrolysis and incineration systems. The burdens for the pyrolysis technology a higher compared to those of the incineration

technologies, but the credits are around twice as high for pyrolysis compared with the incineration systems.

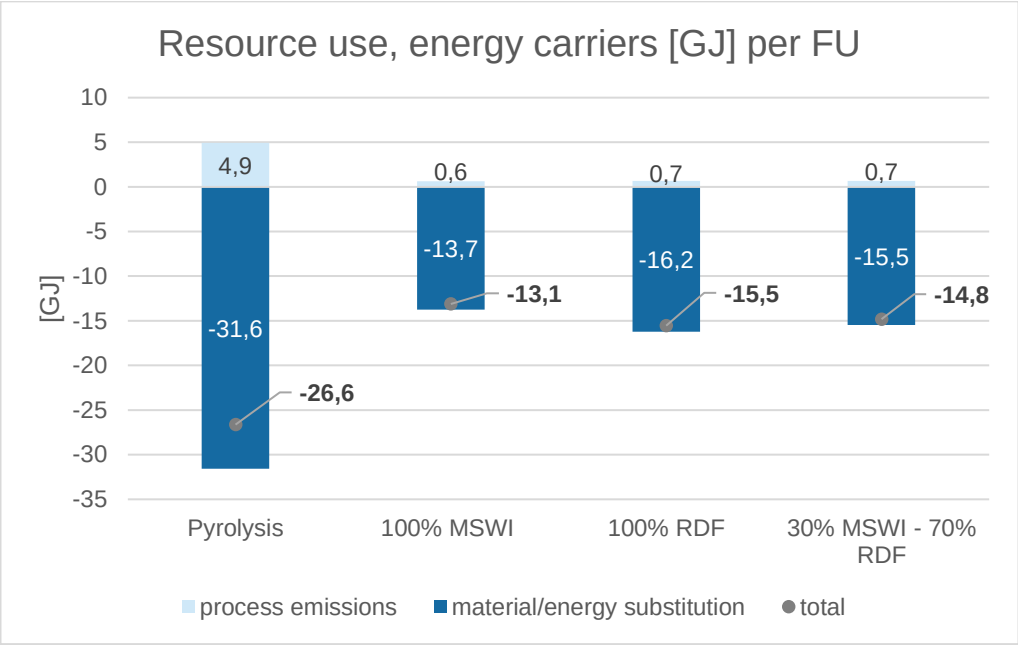


Figure 2-5 EF 2.0 Resource use, energy carriers [GJ] per FU – case study #1

Analysis:

In the pyrolysis systems, crude oil, as non-renewable energy resources, dominates the total GJ result. In the incineration systems, natural gas, as non-renewable resources, dominates the total GJ result.

The figure above shows that material and energy substitution is the main driver for all technologies under evaluation. Impacts in the material substitution for the pyrolysis technology are due to the naphtha credits. Impacts in the energy substitution for the incineration technologies are due to electricity and thermal energy credits. Contribution analysis shows that around 33% of the impact comes from the electricity credits and 67% from the thermal energy credits (30% MSWI and 70% RDF).

Electricity credits are dominated by the electricity from natural gas, from lignite and from hard coal which represent about 84% of the total electricity credits. Thermal energy credits are dominated by the thermal energy from natural gas which represents about 75% of the thermal energy credits.

In the process emissions for pyrolysis technology, the total result is 4,9 GJ. Contribution analysis shows that 13% is associated with waste collection, sorting, extra-sorting and transportation and 87% from the pyrolysis technology, thereof 34% from the pyrolysis process and 53% from the purification process (mainly due to the use of sodium methylate). In the process emission, for the incineration technologies (MSWI and RDF) the total result is 0,7 GJ. Contribution analysis shows that 74% of the energy used is from the incineration technology and 26% is associated to the waste collection, sorting, extra-sorting and transportation. Additionally, there are electricity and thermal energy credits from the thermal treatment of impurities in the extra sorting step, credits are 1253 GJ (30% MSWI and 70% RDF).

Overview of selected impact categories

The following graphics give an overview on all selected impact categories for the assessed systems.

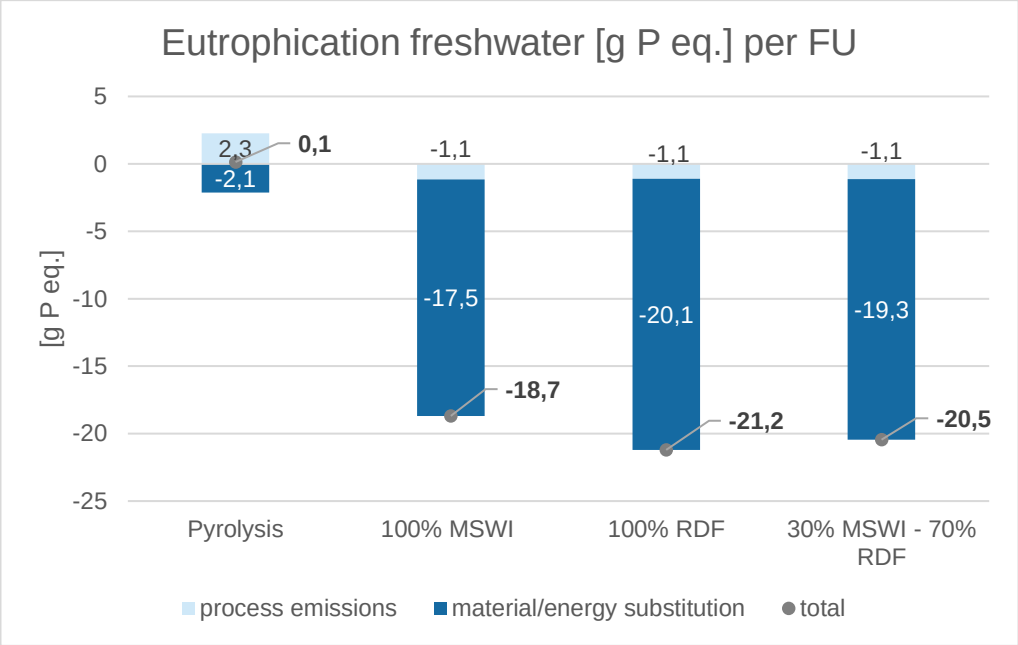


Figure 2-6 EF 2.0 Eutrophication freshwater [g P eq.] per FU – case study #1

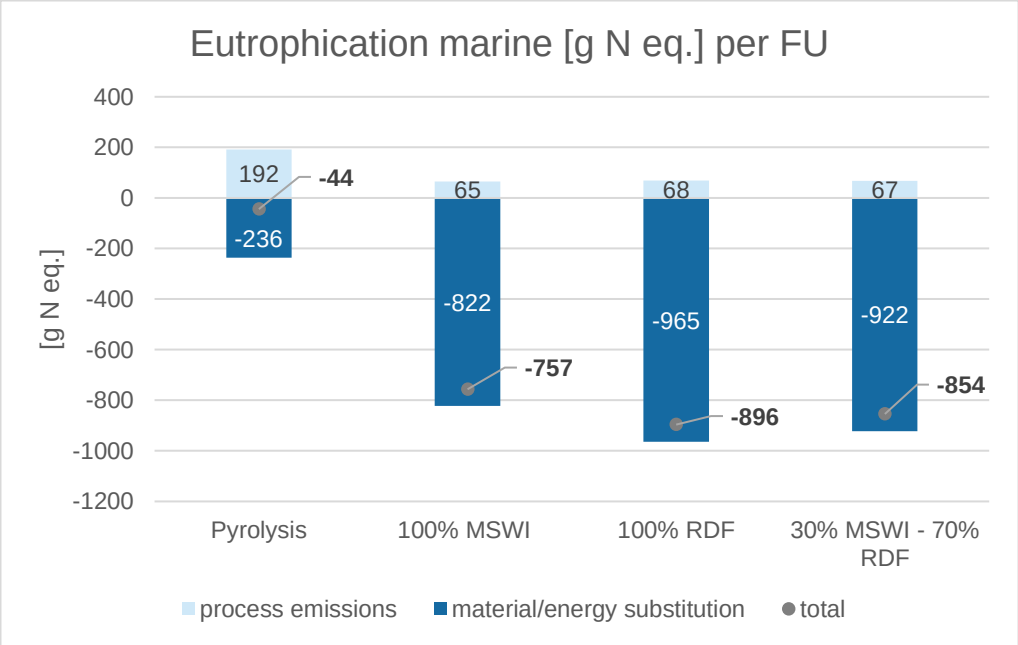


Figure 2-7 EF 2.0 Eutrophication marine [g N eq.] per FU – case study #1

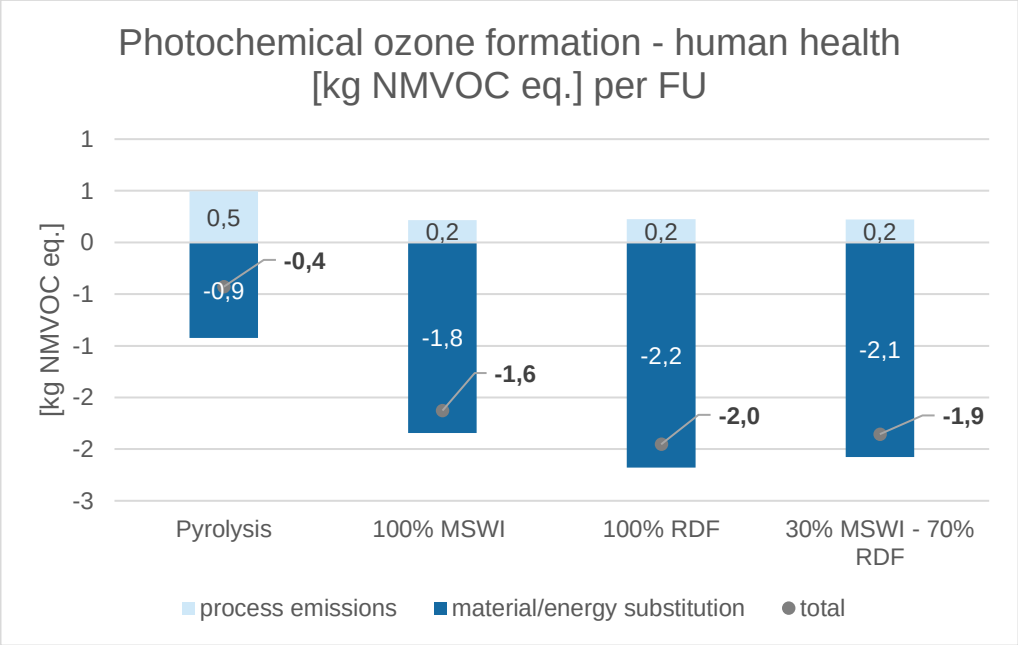


Figure 2-8 EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.] per FU – case study #1

The results for eutrophication freshwater, eutrophication marine and photochemical ozone formation - human health show the same trend as those for acidification, terrestrial and freshwater. The incineration technologies profit from the recovered energy that is substituting thermal energy and electricity. The contribution to the credits substitution of thermal energy are greater than those from substitution of naphtha. As such, the incineration systems have significantly better results than the pyrolysis system. All options show net-negative impacts.

The results of these indicators for the pyrolysis system are influenced by a mix of factors comparable to the acidification terrestrial and freshwater result: in the process emission the contribution analysis shows that major contributors are the energy consumptions in pyrolysis oil process (mainly electricity) and purification process (mainly thermal energy) , the consumption of sodium methylate in the purification step is also relevant. In the material substitution the main role is from the naphtha credits.

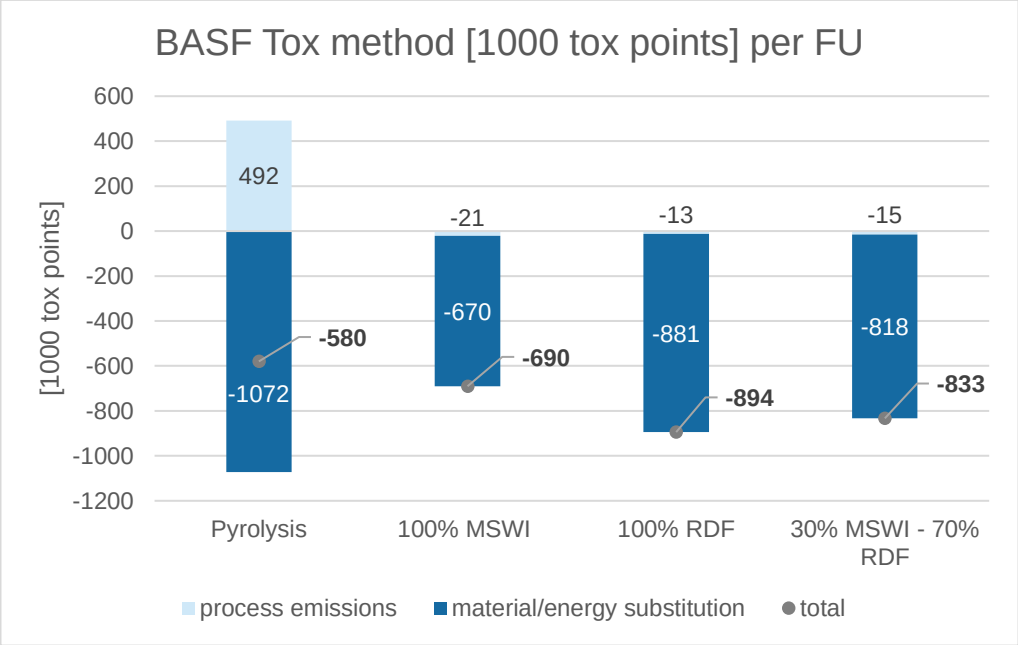


Figure 2-9 BASF Tox method [1000 Tox point] per FU – case study #1

The toxicity results in the pyrolysis technology are driven by the naphtha credits and the pyrolysis oil process. In the incineration technologies drivers are the thermal energy and electricity credits. All incineration options show lower results in terms of human toxicity than the pyrolysis option.

Analysis of ReCiPe indicators in comparison to assessed impact categories

The ReCiPe indicator results are shown in Annex A. When comparing the assessed categories from Table 2-8 with the ReCiPe indicators, the same general trends are observed, with the exception of some toxicity indicators. The “human toxicity - non cancer” indicator in ReCiPe follows the same trend as the BASF toxicity method. However, the MSWI system has better results for the indicator “human toxicity – cancer” compared to the pyrolysis system. The EF2.0 indicators for human health effects have opposite trends compared to ReCiPe. “Cancer human health effects” follows the same trend as BASF human toxicity whereas “non-cancer human health effects” do not. At present, toxicity methods in LCA do not deliver robust results and therefore those results can certainly give additional information for the interpretation of results but should be handled with care in context of drawing conclusions.

2.4.2. Scenario Analysis

Strategies on cutting greenhouse gas emissions which are aiming on short- and long-term targets have been defined by the European Commission (https://ec.europa.eu/clima/policies/strategies_en). Climate Change is therefore a key performance indicator in the waste-to-energy and chemical sectors which is extensively discussed within the group of external and internal stakeholders defined as the intended audience of this study due to the challenges around climate change. As a consequence, the scenarios are analysed for the result indicator climate change based on CO_2-eq only.

Scenario group 1: Technologies considered in the product system due to system expansion

For a description of this scenario group, please see section 2.2.4.

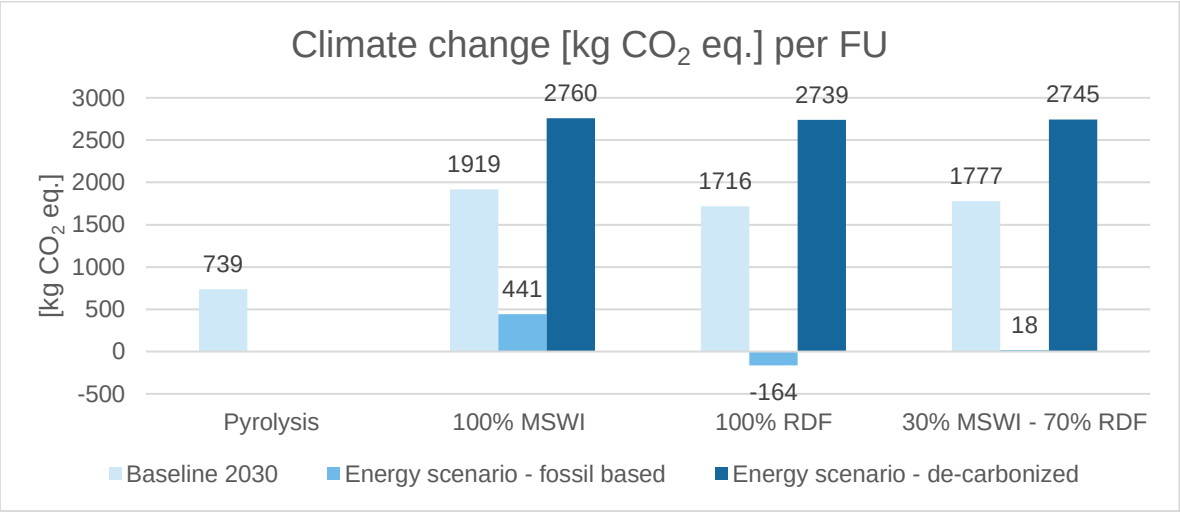


Figure 2-10 Scenario group 1 – case study #1 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

This scenario is used to derive potential LCA results of the assessed systems, in relation to the electricity mixes in other European countries besides Germany and the future beyond 2040, with >20 years considered to be “mid-term” in relation to sectoral developments.

The range of climate change results for the incineration technologies is very large, considering the extreme cases for the energy credits. The fossil-based scenario has significantly better climate change results than the pyrolysis system. This scenario might be representative for parts of Eastern Europe. The de-carbonized energy credit scenario could represent the mid-term future for some European countries (e.g. Scandinavian countries) in the year 2040 and beyond. The climate change results for the incineration systems in 2030 still benefit from partly fossil based energies. In the future, as de-carbonization of the industry is the mid-term goal for Germany and other European countries, the incineration systems hardly benefit concerning climate change results from the energy credits.

Thus, the trend in comparison of the different systems is significantly affected by the energy credits in the incineration system.

Analysis of the effect on the total results when applying different energy credits

The impact of recovered energy on the overall results for the incineration systems is generally high. But the level of impact varies from indicator to indicator as the result analysis shows in the previous

sections. Scenario group 1 analyses the effects of the different energy credits –with a focus on climate change in the interpretation section:

- Energy mix for thermal energy and electricity based on 2030 situation
- Energy mix for thermal energy and electricity – de-carbonized situation (100% renewable)
- Energy mix for thermal energy and electricity – fossil based (100% fossil).

The following graph displays the results for the selected indicators (except for human toxicity) to show the effects of the different energy mixes which are applied for energy substitution (credits).

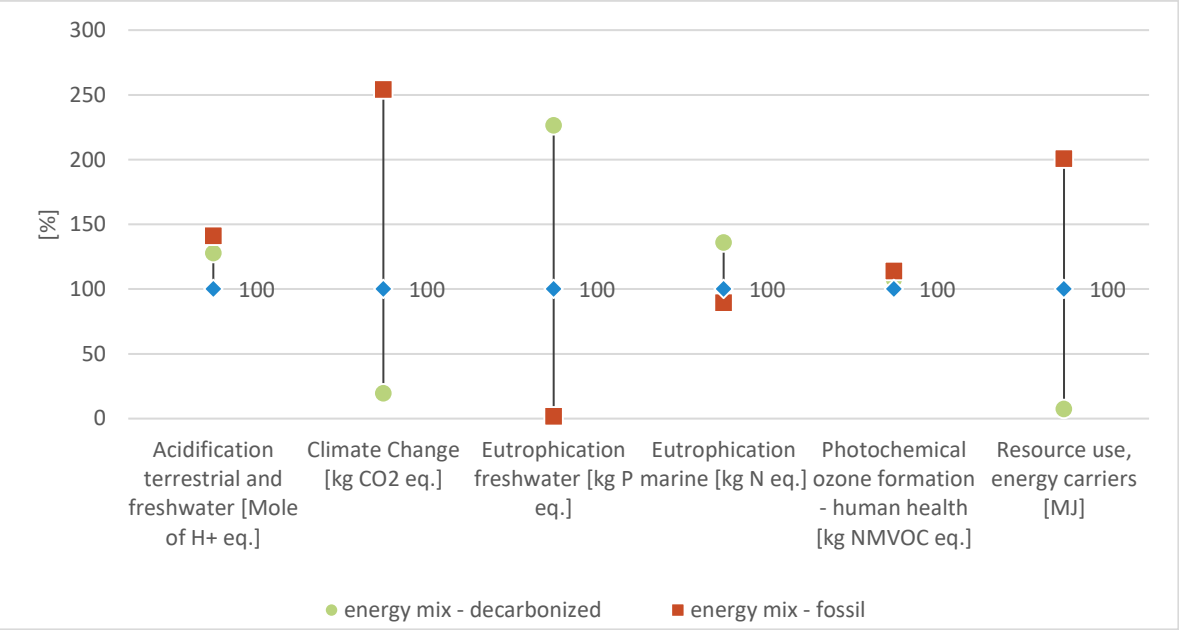


Figure 2-11 Effect of different energy mixes on selected indicators

The energy mixes are calculated based on shares from the incineration of high-calorific MPW as applied in the study – ca. 85% thermal energy, ca. 15% electricity. The decarbonization is visible in the analysis, the lower the share of fossil resources, the lower the effect on CO2-equivalents and vice versa. The same is logically true for fossil resource use. The amplitude in both cases is comparably high.

The effect of the energy mixes on other indicators besides climate change, such as acidification, eutrophication and photochemical ozone formation is different. The amplitude of the eutrophication freshwater result is similar like climate change but inverted. The lower the share of fossil resources in the energy mix, the higher the effect on P-equivalents. The latter is also true for eutrophication marine, while the amplitude of the EP marine result is much lower compared to climate change and EP freshwater results (comparably to POCP and AP results). Thus, decarbonization does not mean at the same time de-phosphorization, or de-nitrogenization or de-sulfurization but in some cases the opposite. This effect is important to consider when analysing results that are not CO_2-driven including substitution of energies. The crediting effect for most indicators besides climate change and fossil energy resource use is relatively high compared to CO_2 equivalents and GJ, therefore the system that uses energy credits profits from those credits even more with a transformed energy market.

Scenario group 2: target feedstock – economic allocation

For a description of this scenario group, please see section 2.2.4.

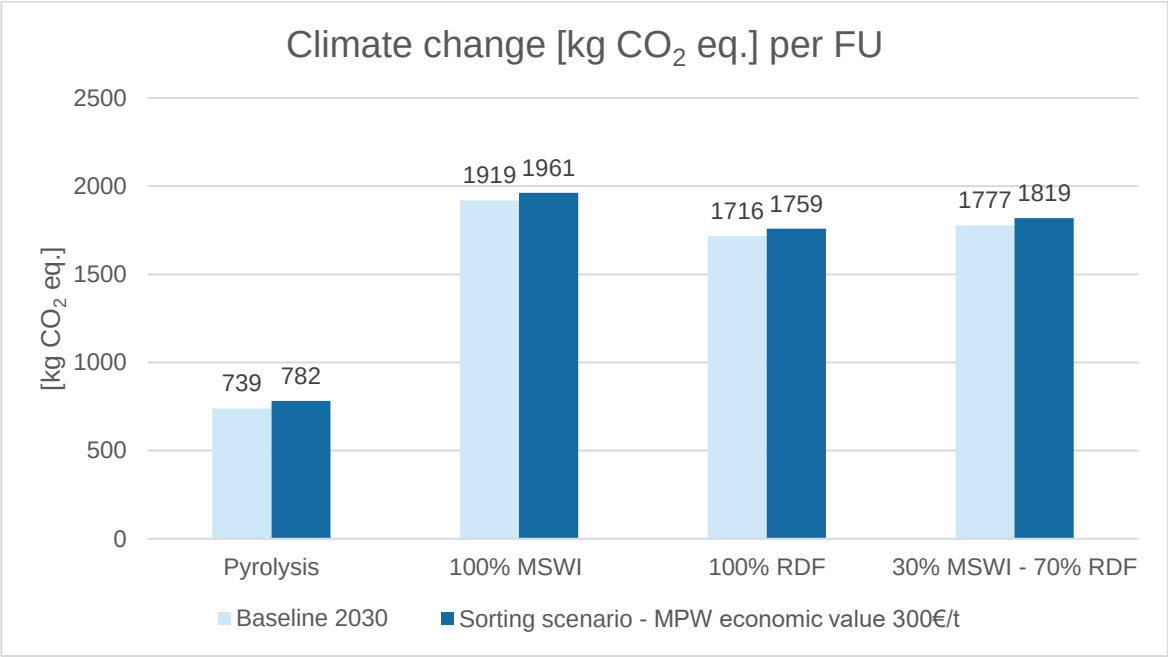


Figure 2-12 Scenario group 2 – case study #1 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

The effect of changing economic values for different waste fractions in the sorting plant is of minor relevance for the total climate change results. With the increasing economic value for MPW (300 Euro instead of 110 Euro), the climate change results for the pyrolysis system increase by 6%. As the overall results have shown in the previous section, the contribution of waste collection, sorting, extra sorting and transportation is around 20% of the climate change result regarding the “process emissions” (excluding the credits due to substitution).

Scenario group 3: Target feedstock - extra effort in the extra sorting step

For a description of this scenario group, please see section 2.2.4.

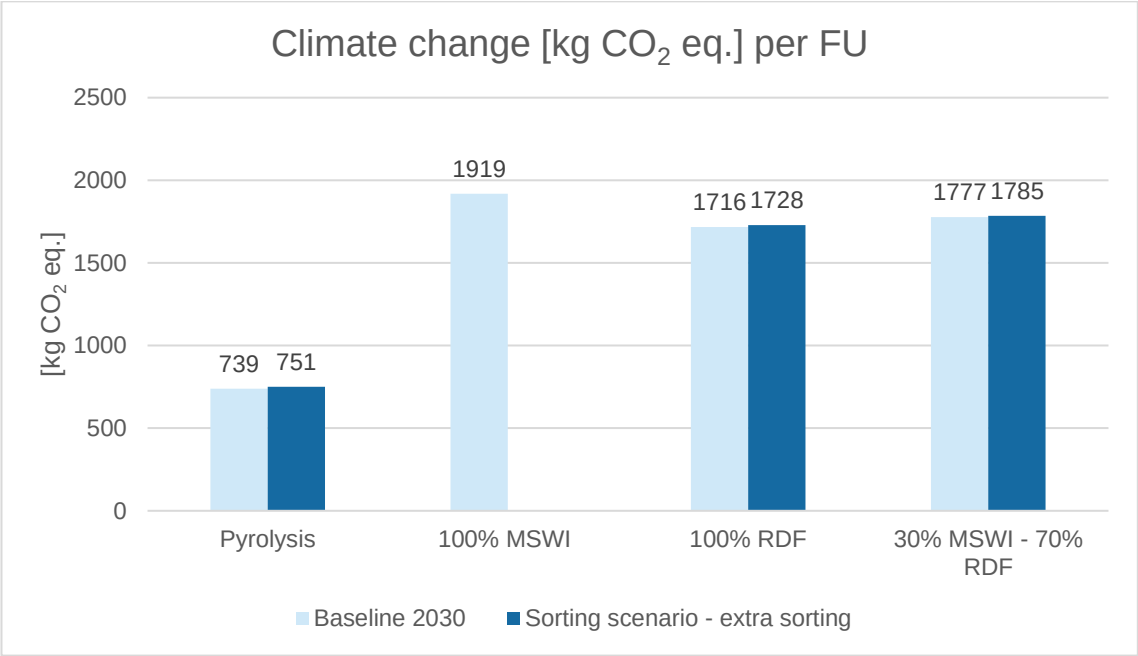


Figure 2-13 Scenario 3 – case study #1 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

The higher energy consumption for the extra sorting of MPW in the pyrolysis system has a negligible effect on the total climate change results. With the increasing electricity consumption (factor 3 higher), the climate change result for the pyrolysis system increases by less than 1%. As the overall results have shown in the previous section, the contribution of waste collection, sorting, extra sorting and transportation is around 20% of the climate change result regarding the “process emissions” (excluding the credits due to substitution).

Scenario group 4: Core technologies considered in the product system - purification efficiency

For a description of this scenario group, please see section 2.2.4.

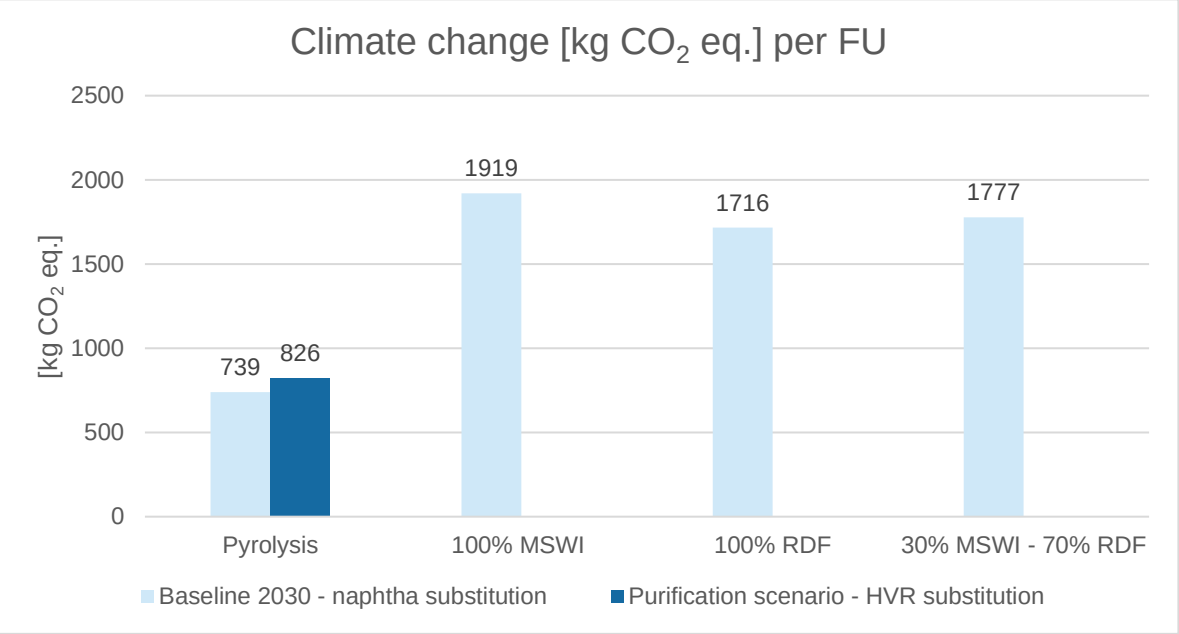


Figure 2-14 Scenario 4 – case study #1 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

Figure 2-14 shows that the total climate change results for the pyrolysis systems are significantly affected by the different substituting material. The climate change result increases by 11%. The trend in comparison of both systems is not affected by this scenario.

Scenario group 5: Core technologies considered in the product system – pyrolysis efficiency

For a description of this scenario group, please see section 2.2.4.

As the following graph shows, the total climate change results for the pyrolysis systems are very sensitive to changes in carbon conversion efficiency. The climate change result is reduced by 27% when the efficiency is improved to 77% and reduced by 68% when the efficiency is further improved to 87%.

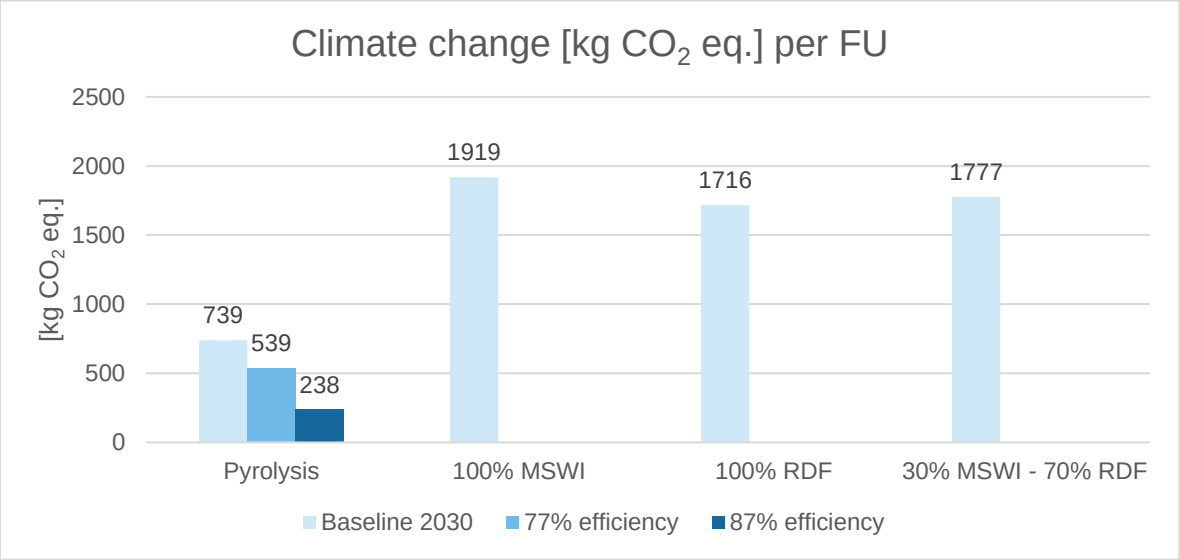


Figure 2-15 Scenario 5 – case study #1 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

Scenario group 6: cement kiln scenario

For a description of this scenario group, please see section 2.2.4.

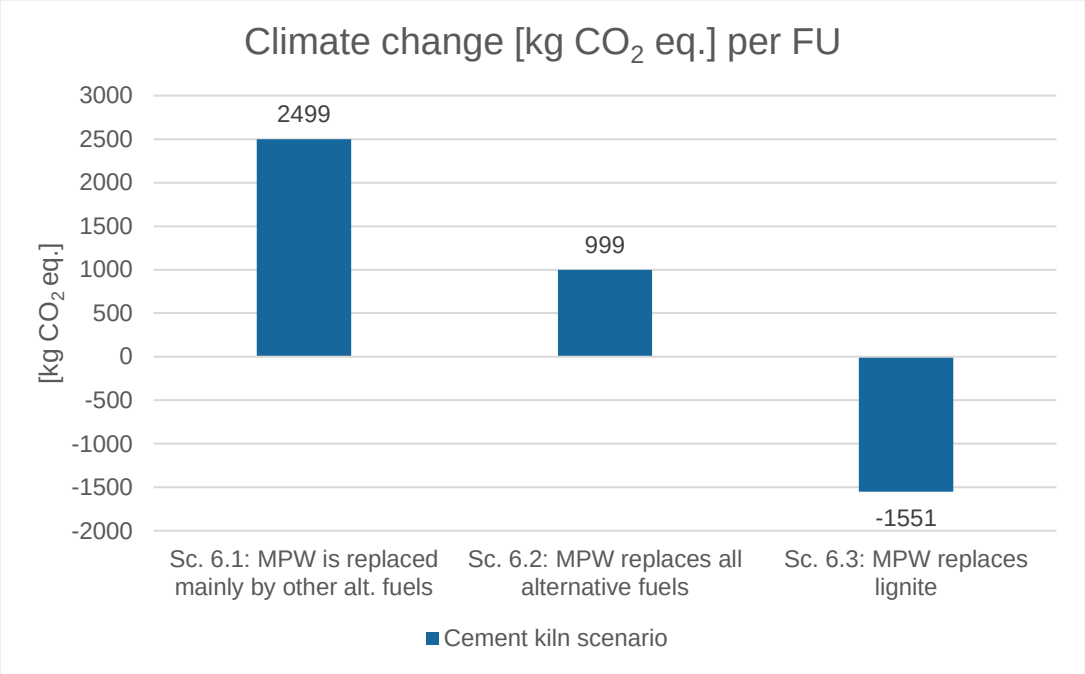


Figure 2-16 Scenario 6 – case study #1 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

The range of results for the cement kiln scenarios is very high. The differences in climate change results of scenarios 6.1, 6.2 and 6.3 are mainly affected by the assumptions concerning the adapted emission profile of the alternative fuels. So, the uncertainty of those scenario results is relatively high.

The GHG emissions rise in scenario 6.1 as high-calorific MPW is mainly replaced by a mix of other alternative fuels, which are characterized by partly a lower calorific value as MPW. They decrease again if all alternative fuels are replaced by MPW in scenario 6.2. However, the climate change result is still very high at 999 kg CO_2 eq.

The results of scenario 6.3 show that the cement kiln is beneficial if lignite is replaced by mixed plastic waste.

The authors of the study don't recommend using the results of this scenario analysis as the basis for decisions as the uncertainty of the data applied and assumptions made, and the resulting volatility of total climate change results, is very high.

More sub-scenarios or variations of the described sub-scenarios for the cement kiln are conceivable. However, with the setup of those sub-scenarios, the authors aimed to check relevant key parameters in different conceivable directions to analyse the effect of MPW as alternative fuel in cement kilns.

3. Case study #2 – product perspective - virgin-grade quality

3.1. Goal of the Study

Reasons for carrying out the study

General reasons for carrying out the study which are applicable for all three case studies are described in section 1.3.

As second part of the study "Evaluation of pyrolysis with LCA", the case study #2 occupies the product perspective. The goal of case study #2 is to evaluate the environmental impacts of pyrolysis as part of the value chain to produce an exemplary chemical product in virgin-grade quality. The baseline for the evaluation is the anticipated situation in 2030 in Germany.

The technical route to produce a chemical product in virgin-grade nowadays and anticipated to be still in 10 years in Germany is (for selection of comparative system):

- Virgin plastic production

LDPE granulate is selected as exemplary chemical product.

Scenarios are assessed to check the influence on the overall results of predictable variations of developments compared to the baseline situation in the considered technologies. The scenarios are used as well to derive potential LCA results of the assessed systems in the context of other European countries than Germany or even further in the future, up to an anticipated situation in 2050.

Intended audience

The intended audience of the study are internal and external stakeholders in Europe regarding waste management, plastic waste treatment and circular economy in the chemical industry.

Intended application

The intended application of the study is to enrich the discussion about environmental evaluation of pyrolysis in the context of plastic waste recycling resp. end of life of plastic products with LCA-based data and results.

The results are intended to support comparative assertions and intended to be disclosed to the public The study has been conducted according to the requirements of ISO 14040 (ISO 14040, 2006) and 14044 (ISO 14044, 2006). The requirements of (ISO/TS 14071, 2014) are respected.

3.2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

3.2.1. System boundaries, Product Systems, Product Function(s) and Functional Unit

The function of the product system is the production of LDPE in virgin-grade quality in 2030 in Germany.

Two selected production technologies for virgin-grade LDPE are assessed:

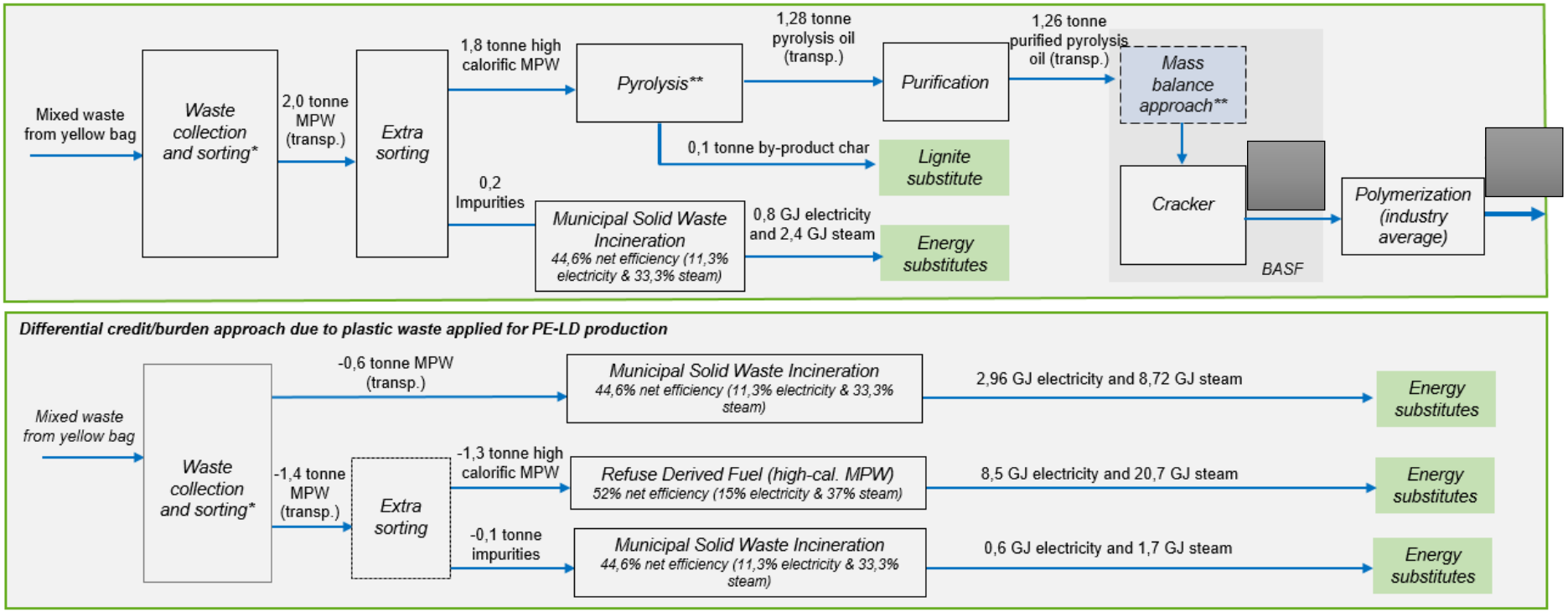
- Pyrolysis and subsequent purification to produce a naphtha substitute which is fed into the steam cracker followed by the polymerization step as basic system and virgin LDPE production with fossil-based naphtha as feedstock as comparative system. The feedstock for pyrolysis is MPW, comparable to the case study #1.
- The conventional chemical pathway by using Naphtha from primary fossil resources to produce conventional virgin LDPE

The functional unit is defined as *1 tonne of LDPE granulate produced in virgin-grade quality* (reference flow is the same as functional unit).

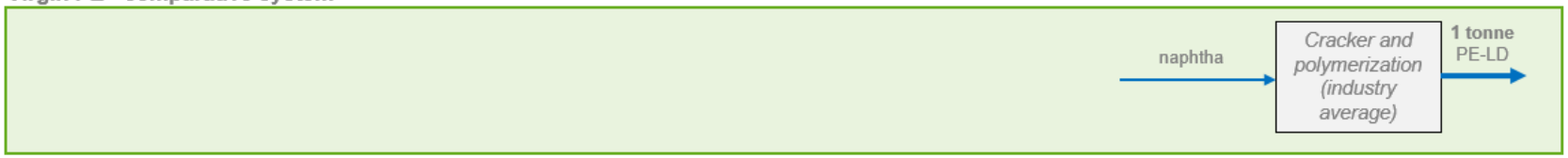
The function and functional unit are consistent with the defined goal of the study.

As recommend by the review panel during the goal and scope workshop as part of the review process, the basic system comprises a differential credit/burden approach. A system expansion is applied to account for the waste incineration of MPW which is prevented, a combination of 30% MSWI and 70% RDF is considered. The amount of MPW which is required in pyrolysis to produce 1 tonne of virgin-grade LDPE granulate determines the amount for which incineration in 30% MSWI and 70% RDF plant is prevented.

Chemical Recycling – basic system



Virgin PE - comparative system



System boundaries | Foreground and background data | Substitute / credits

transp. = transported
* Economic allocation for waste fractions in sorting plant
** Substitution of naphtha by waste-based chemical
*** Mass losses due to process efficiency

Figure 3-1: System boundaries – case study #2

The system boundaries of the basic and comparative system are shown in the Figure 3-1. The complete system including the system expansion due to material and energy substitution and the prevented incineration of MPW and RDF is displayed. The functional unit is 1 tonne of virgin-grade LDPE produced. Whenever transportation of materials or intermediates takes place, it is indicated next to the substance name in the system boundaries ("transp."). The type of transportation and assumed distances are described in the Life Cycle Inventory Analysis section (section3.3).

Inclusions and exclusions are summarised in theTable 3-1. No data were available for the elements of the systems that are excluded. However, it is assumed that the contributions to the overall results of case study #2 of the exclusions are minor.

Table 3-1: Inclusions and exclusions in system boundaries - case study #2

Included		Excluded	
✓	Mixed waste collection and transportation to sorting plant	×	Capital goods
✓	Mixed waste sorting	×	Infrastructure
✓	MPW transport to extra sorting resp. MSWI	×	Employee commute
✓	MSWI technology with energy recovery (both for high-calorific waste and municipal waste)	×	Any administrative activities
✓	Pyrolysis technology with 1 main product and 1 by-product	×	Baling press at mixed waste collection plant
✓	Transport of pyrolysis oil to purification		
✓	Purification of pyrolysis oil		
✓	BASF steam cracking		
✓	Polymerization of ethylene to LDPE		
✓	Prevented activities due to MPW applied for LDPE production		
✓	Energy/fuel substitution of lignite, electricity and thermal energy		
✓	Industry average LDPE production (cracking of fossil-based naphtha and Polymerization)		

Production of capital equipment, infrastructure and impacts associated with employee commuting and administrative activities have been excluded as these should not be relevant when allocated to the quantities of waste being processed.

No data were available for the baling press, but this is likely to be insignificant compared other emissions from waste processing via either the base case or comparative scenario. In any case, this process would be applied to waste input to both assessed disposal routes and so does not introduce bias into the study.

The basic system and comparative system are equivalent in the following aspects:

- in the amount and type of product – LDPE granulate in virgin-grade quality,
- in the system boundaries applied: entire value chain for both production technologies for LDPE assessed acknowledging the prevented incineration of MPW in the basis system, and
- in the foreground and background data applied.

Additionally, there is no omission purposely of additional functions in the compared systems.

Table 3-2: Systems of case study #2

Case 2 - System	Short description
Basic system	The defined waste feedstock (MPW) is used in pyrolysis to produce virgin-grade LDPE. Extra sorting of MPW is necessary to meet the feedstock requirements of the pyrolysis technology. The resulting pyrolysis oil undergoes a purification step. Purified pyrolysis oil is then used as feedstock in steam cracker to produce ethylene after which it is transformed in a polymerization step to LDPE granulate. The production system is expanded by the activities associated to prevented waste incineration in MSWI and RDF plants including energy recovery of the amount of waste feedstock (MPW) that is used in pyrolysis. The resulting energy (mix of thermal energy and electricity) is recovered and substitutes for thermal energy and electricity in the German market.
Comparative system	Virgin-grade LDPE is produced using virgin (fossil-based) feedstock (naphtha). Industry-average processes for steam cracker (ethylene production) and polymerization (LDPE production) have been applied.

3.2.2. Description of the representativeness of the chosen products and systems

Definition of the baseline systems – situation in 2030 in Germany

The technical development from now until 2030 of the assessed technologies is considered. It is described in the following how that is implemented in the case study to define the baseline in 2030.

Core technologies considered in the product systems:

For the pyrolysis technology, the purification technology, the MSWI and the RDF technology – please see section 2.2.2.

The steam cracker process at BASF is applied based on primary data from 2018. The Cracker I at BASF Ludwigshafen was put into operation in 1965, the Cracker II in 1980. The process is continuously optimised. Thus, this technology still might be slightly optimised during the next 10 years. The assumption of applying 2018 data for 2030 for the basic system is considered as conservative approach in the context of the goal and scope of case study #2.

The virgin LDPE production is based on industry-average data of 2018. The basis to produce PE is crude oil. Polyethylene is polymerised from ethylene, which is extracted by cracking naphtha in a steam-cracker. LDPE is produced by a high-pressure process. In the baseline, the current industry-average production data of LDPE are applied as well for 2030 as a prediction of industry-wide changes in future chemical production is difficult.

Technologies considered in the product systems due to system expansion:

For the generation of electricity and thermal energy – please see section 2.2.2.

Further technologies as part of the systems:

For the sorting plant, the plant for extra sorting and transportation - please see section 2.2.2.

Definition of the baseline products – situation in 2030 in Germany

Description of selected exemplary chemical product – virgin-grade LDPE

- LDPE is a thermoplastic made from the monomer ethylene.
- LDPE is a widely used commodity plastics worldwide.
- BASF delivers ethylene as the monomers. LDPE production is based on stream cracker and it represents the simplest polymerization process.
- LDPE is widely used for manufacturing lightweight packaging - various containers, dispensing bottles, wash bottles, tubing, wraps. Its most common use is in plastic bags.
- It is deemed appropriate to transfer the described current situation to 2030.

3.2.3. Key performance characteristics

For characteristics of mixed plastic waste (MPW), high-calorific mixed plastic waste, (residual) municipal waste and purified pyrolysis oil – please see section 2.2.3.

Virgin grade LDPE granulate – with focus on possible application as packaging material

- LDPE is defined by a density range of 0.917–0.930 g/cm^3
- Chemical resistance of LDPE:
  - Good resistance to alcohols, dilute alkalis and acids.
  - Limited resistance to aliphatic and aromatic hydrocarbons, mineral oils, oxidizing agents and halogenated hydrocarbons.
- Temperature resistance up to 80°C continuously and 95°C for shorter times.
- High impact strength at low temperature, good weatherability.
- Excellent electrical insulating properties.
- Very low water absorption.
- FDA (U.S Food and Drug Administration) compliant – can be safely used when in contact with food products (also call “food-grade”).
- Transparent in thin film form.

3.2.4. Scenario description

Scenario group 1: Technologies considered in the product systems due to system expansion

Scenario group 1 assesses the influence of national energy grid mixes, both for electricity and thermal energy, in terms of time coverage and geographical coverage within case study #1 with a link to European countries besides Germany and a link to “mid-term” future developments (> 20 years from now) on the energy market. It focuses on the recovered energies that are substituted and result in environmental credits in the system. Two extreme scenarios concerning CO_2-eq. emissions have been defined with energy produced conventionally from base load energy plants. One assesses the GHG impact on the comparative systems if the recovered energies and electricity are substituted with fossil energies and electricity, the other one with renewable (see Table 3-3).

Table 3-3 Case study #2, Scenario group 1 overview: Technologies considered in the product systems due to system expansion

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 1	✓ Pyrolysis × Virgin PE	**Base case**	Baseline 2030	Recovered energies and electricity substitute anticipated future energy and electricity mixes for Germany in 2030 (see tables 2-11 and 2-12).
		Scenario 1	Energy credit, fossil	Recovered electricity substitutes electricity from lignite. Recovered heat substitutes thermal energy from heavy fuel oil (HFO).
		Scenario 2	Energy credit, de-carbonized	Recovered electricity substitutes electricity from hydro power. Recovered heat substitutes thermal energy from renewable resources (biogas and biomass).

Scenario group 2: Target feedstock – mixed plastic waste (MPW):

This scenario focusses on the composition of MPW that is considered to be comparable in 2019 and 2030 in Germany. However, a scenario has been modelled that covers two different aspects:

- It considers a different composition in 2030 with an estimated 30% higher content of PET that results in higher extra sorting effort compared to the baseline scenario to achieve the quality requirements for the target feedstock into pyrolysis plant.
- Also, it considers an improving sorting technology that leads to a higher share of mono-material waste fractions and a decreasing quality of MPW fraction. So, the scenario simulates an increasing extra sorting effort after the sorting plant to improve the characteristics of MPW to a high-calorific MPW (Table 3-4).

Table 3-4 Case study #2, Scenario group 2 overview: Target feedstock – mixed plastic waste (MPW)

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 2	✓ Pyrolysis × Virgin PE	**Base case**	Baseline 2030	Additional effort of +33% electricity consumption of extra sorting after the sorting plant.
		Scenario	Extra sorting effort (+100%)	Additional effort of +100% electricity consumption of extra sorting after the sorting plant.

Scenario group 3: Virgin production of LDPE in 2030

Base case for virgin production: industry-average data based on 2018 applied.

This scenario is not calculated using a prediction of the future virgin PE production. But it is obvious, that even if this production improves by 50% - which is highly unlikely - the trend of the total climate change result in comparison of the pyrolysis system including incineration which is prevented is not affected.

Table 3-5 Case study #2, Scenario group 3 overview: Virgin production of LDPE in 2030

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 3	× Pyrolysis ✓ Virgin PE	**Base case**	Baseline 2030	LDPE production data based on industry averaged data in 2018 (Sphera, 2019).
		Scenario	Improved LDPE production	Improved LDPE production to be seen as future production.

3.2.5. Time Coverage

The intended time reference is the year 2030. All elements in the assessed baseline systems are adapted as good as possible to this time reference as described in section 2.2.2 and 3.2.2.

The scenarios partly prolong the time coverage to at least 2040.

3.2.6. Technology Coverage

The intended technology references cover the production of virgin-grade LDPE in Germany in the year 2030:

- Pyrolysis with MPW as feedstock and a purification step combined with cracker and polymerization
- virgin production based on naphtha
- prevented MPW incineration incl. energy recovery

Further technologies are covered in case study #2 which are linked to those core technologies:

- generation of electricity in 2030 based on 100% fossil energy resources and 100% renewable energy resources
- generation of thermal energy in 2030 based on 100% fossil energy resources and 100% renewable energy resources
- Sorting plant of mixed waste collected from household (including mainly lightweight packaging wastes)
- Extra sorting of mixed plastic waste to generate high-calorific mixed plastic waste (feedstock for pyrolysis technology)

3.2.7. Geographical Coverage

The intended geographical reference is Germany.

The scenarios extend the geographical coverage to European countries besides Germany.

3.2.8. Allocation

For multi-output allocation and End-of-Life allocation – please see section 2.2.8

The concept of “mass balance” as described in Jeswani et al. (2019) is applied for the ethylene production (BASF steam cracker). The principle of the mass balance approach is depicted in Figure 3-2. Mass flows of naphtha and natural gas are tracked in the LCA modelling software throughout the value chain. For each product, in this case ethylene, the amount of fossil based naphtha and

natural gas (material use part only) which has been fed at one point into the cracker can be read out. The cracker input material, mainly naphtha, is then substituted by purified pyrolysis oil based on the lower heating value. As there is a physical connection between the purified pyrolysis oil and the cracker, the compliance with mass balance calculation rules is fulfilled.

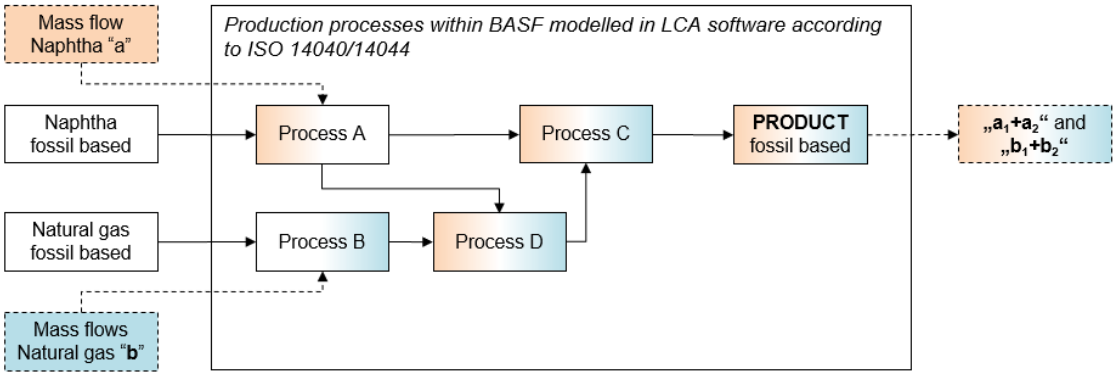


Figure 3-2 Mass balance approach - principle

3.2.9. Cut-off Criteria

No cut-off criteria are defined for this study. As summarized in section 0 and 3.2.3, the system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The influence of these proxy data on the results of the assessment is discussed in Chapter 5.

3.2.10. Selection of LCIA Methodology and Impact Categories

Please see section 2.2.10.

3.2.11. Data Quality Requirements

Please see section 2.2.11.

3.2.12. Type and format of the report

Please see section 2.2.12.

3.2.13. Software and Database

Please see section 2.2.13.

3.2.14. Critical Review

Please see section 2.2.14.

3.3. Life Cycle Inventory Analysis

3.3.1. Data Collection Procedure

Please see section 2.3.1.

3.3.2. Foreground System

Processes included in the foreground system are described in the following sections.

Mixed waste collection

Please see section 2.3.2.

Mixed waste sorting

Please see section 2.3.2.

MPW extra sorting

Please see section 2.3.2.

Chemical Recycling – Pyrolysis

Please see section 2.3.2.

Cracking

Purified pyrolysis oil is further fed into the cracker to produce ethylene. Primary data from BASF have been used in the model, the unit process information is provided in Annex C. The concept of “mass balance” as described in Jeswani et al.(2019) is applied for the ethylene production. The cracker input material naphtha and natural gas are substituted by purified pyrolysis oil based on their lower heating value as approximation for of their chemical properties, as suggested by Jeswani et al. (2019)

Purified pyrolysis oil is transported to cracking plant 50 km (Dr Stefan Strege (BASF, Technical information from BASF experts, 2019)), a diesel-driven Euro 6 truck with a capacity of 28t is used. Empty return transport during collection and transportation of mixed waste is considered. Secondary data from the GaBi databases for transportation vehicles and fuels are used, these databases are representative for vehicle types, sizes and technologies.

Polymerization

Ethylene is transported from cracking to the polymerization plant 50 km (Dr Christian Krüger (BASF, Technical information from BASF experts, 2019)), a diesel-driven Euro 6 truck with a capacity of 28t is used. Empty return transport during collection and transportation of mixed waste is considered. Secondary data for polymerization process from the GaBi database was used in the model. Secondary data from the GaBi databases for transportation vehicles and fuels are used, these databases are representative for vehicle types, sizes and technologies. Documentation for all GaBi datasets can be found online (Sphera, 2019).

Municipal Solid Waste Incineration

Please see section 0.

3.3.3. Background System

Processes included in the background system are described in the following sections.

Fuels and Energy

Please see section 0.

Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2018 database.

Table 3-6 shows the most relevant LCI datasets used in modelling the product systems.

Table 3-6: Key material and process datasets used in inventory analysis – case study #2

Location	Dataset	Data Provider	Reference Year	Proxy?
DE	Waste incineration (municipal waste)	Sphera	2018	no
DE	Nitrogen allocated by volume	BASF	2018	no
DE	Compressed air	BASF	2018	no
DE	Hydrogen 25 bar	BASF	2018	no
DE	Sodium methylate, 30% solution in Methanol	BASF	2018	no
DE	Tap water from groundwater	Sphera	2018	no
DE	Demineralized Water LU (Water 0% consumptive)	BASF	2018	no
DE	Municipal wastewater treatment (mix)	Sphera	2018	no
DE	Lignite mix	Sphera	2016	no
DE	Naphtha at refinery	Sphera	2016	no
DE	Nitrogen via cryogenic air separation production mix, at plant liquid	Sphera	2018	no
DE	Residues	BASF	2018	no
DE	Cooling water from river	BASF	2018	no
DE	Natural gas mix	Sphera	2016	no
DE	Sodium hydroxide	BASF	2018	no
DE	Polyethylene Low Density Granulate (LDPE/PE-LD)	Sphera	2018	no
DE	Polyethylene Low Density Granulate – polymerization process	Sphera	2018	no
DE	Heavy Vacuum Residue	Sphera	2019	no

Transportation

Please see section 0.

3.3.4. Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the “outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment”. As the complete inventory comprises hundreds of flows, the below table only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results.

Table 3-7: LCI results of case study #2*

Flow	Unit	Pyrolysis – avoided emissions (30% MSWI, 70% RDF)	Virgin PE
Resources			
Carbon dioxide	kg	2.131,0	122,4
Energy resources			
Crude oil (in MJ)	MJ	4.439,1	35.311,6
Hard coal (in MJ)	MJ	5.622,3	2.015,4
Lignite (in MJ)	MJ	2.293,0	2.435,1
Natural gas (in MJ)	MJ	30.513,1	27.938,0
Uranium natural (in MJ)	MJ	56,6	1.732,0
Emissions			
Inorganic emissions to air			
Ammonia	g	91,6	24,5
Carbon dioxide	kg	-764,5	1.609,5
Carbon dioxide (biotic)	kg	2.143,4	124,3
Carbon dioxide (land use change)	kg	23,0	1,5
Carbon monoxide	g	2.601,2	947,4
Nitrogen dioxide	g	6,0	0,6
Nitrogen monoxide	g	109,9	7,5
Nitrogen oxides	g	4.428,0	1.806,8
Nitrous oxide (laughing gas)	g	245,5	45,3
Sulphur dioxide	kg	2,3	1,2
Organic emissions to air (group VOC)			
Butane (n-butane)	g	43,8	77,0
Ethane	kg	0,1	0,3
Formaldehyde (methanal)	g	27,4	5,4
NMVOC (unspecified)	g	262,3	263,6
Pentane (n-pentane)	g	45,8	30,5
Propane	kg	0,1	0,3
Methane	kg	3,8	7,2
Methane (biotic)	kg	2,1	0,1
VOC (unspecified)	g	1.106,1	0,0
Inorganic emissions to fresh water			
Ammonia	g	0,1	0,9
Chloride	kg	17,3	92,0
Nitrate	g	2.151,7	143,2
Nitrogen	g	2,7	0,1
Nitrogen (as total N)	g	3,4	0,0
Phosphate	g	107,4	7,6
Phosphorus	g	9,6	0,9
Inorganic emissions to sea water			
Chloride	kg	3,3	25,8

* Negative values are due to the system expansion approach for the multioutput processes, see 2.2.8

** Carbon dioxide (resource) has not been corrected in the LCIs of production systems.

3.4. LCIA Results

This chapter contains the results for the impact categories defined in section 2.2.10. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

3.4.1. Overall Results

The results in the graphs have been broken down to show the contribution to the total impacts from activities in both systems such as sorting, transportation, incineration, pyrolysis and purification steps, cracking, polymerization and virgin PE production. A differential credit approach has been applied: some emissions in the pyrolysis system are linked to incineration, which is prevented, so credits have been allocated to the process emissions of incineration “differential credit approach - incineration”. Similarly, some emissions in the pyrolysis system are linked to energy recovery, which is also prevented, so the burdens associated with this process are allocated to the energy substitutions “differential burden approach - energy recovery”.

Whenever the term “significantly” is used, it refers to minimum differences in results of ±10%.

Climate Change

The overall results for climate change show that the pyrolysis option has significant advantages compared to the virgin PE option in terms of CO_2-equivalents per functional unit (1 tonne of LDPE granulate produced in virgin-grade quality).

The process emissions of the chemical system are about 40% higher compared to the virgin PE production. But the dominating effect in the pyrolysis system is emissions due to prevented incineration which are just partly compensated for by the burdens due to energy recovery.

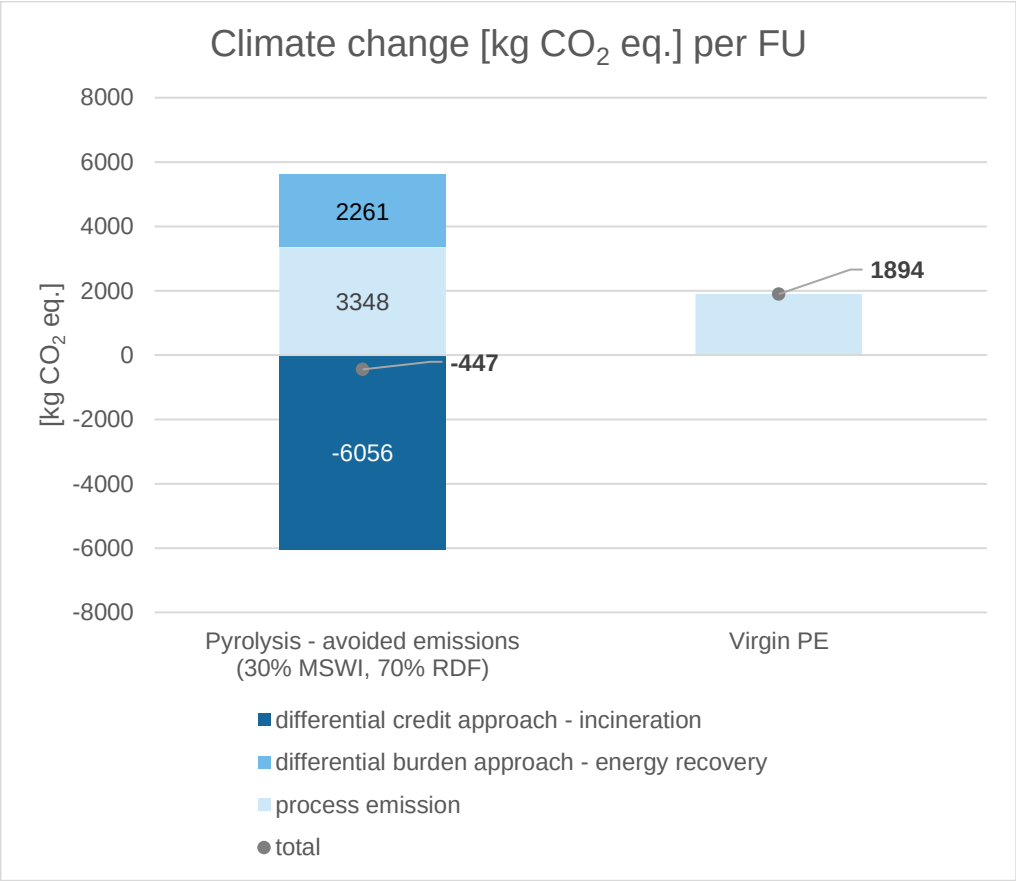


Figure 3-3 EF 2.0 Climate Change total [kg CO2 eq.] per FU – case study #2

Analysis:

Climate change is driven by inorganic emissions to air, primarily carbon dioxide.

The figure above shows that the process emissions in the pyrolysis system is 3348 kg CO_2-eq. Contribution analysis shows that 49% of the impact comes from the pyrolysis process, where the main contributor is direct CO_2 emissions from the pyrolysis step. 21% of the impact comes from the cracker process, 10% from the polymerization process, 6% from purification and 13% from the waste collection and sorting, extra sorting and transportation.

Emissions from the differential burden approach – energy recovery are due to the electricity and thermal energy substitution. Emissions from the differential credit approach – incineration are due to the incineration process.

Acidification

The overall result for acidification shows that the virgin PE option has significant advantages compared to the pyrolysis option in terms of Mole of H^+-equivalents per functional unit (1 tonne of LDPE granulates produced in virgin-grade quality). In total, the mole of H+ equivalents are about 120% higher for the pyrolysis option than the virgin PE option.

The process emissions of the chemical system are about 20% lower compared to the virgin PE production. But the dominating effect in the pyrolysis system is the burden due to energy recovery which is only partly compensated for by prevented emissions due to incineration.

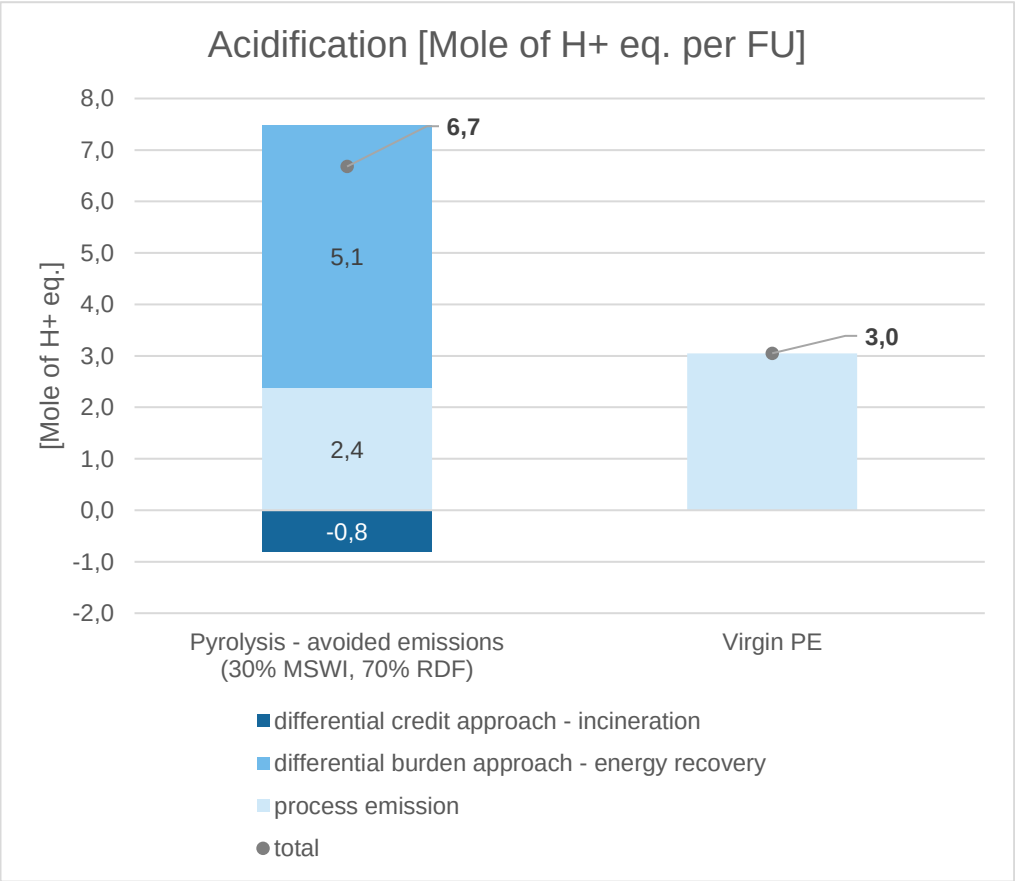


Figure 3-4 EF 2.0 Acidification terrestrial and freshwater [Mole of H^+ eq.] per FU – case study #2

Analysis:

Acidification terrestrial and freshwater is driven by inorganic emissions to air, primarily SO_2 and NO_x emissions

The figure above shows that the differential burden approach – energy recovery is the dominant contributor. The contribution analysis shows that 66% of the impact comes from the thermal energy credits, mainly due to the thermal energy from biogas; and 44% from the electricity credits, bigger contributors are electricity from biogas, from hard coal and lignite.

The second most important contribution comes from process emissions. The contribution analysis shows that 37% of the impact is coming from the pyrolysis process, primarily due to consumption of electricity. 26% of the impact is coming from the cracker process, 26% from the polymerization process and 12% from the purification process. Waste collection and sorting, extra sorting and

transportation processes result in a negative acidification terrestrial and freshwater of -0,21 Mole of H^+ eq. per functional unit, mainly due to the thermal treatment of the losses in the extra sorting step.

Resource use of energy carriers

The overall result for resource use of energy carriers shows that the pyrolysis option has significant advantages compared to the virgin PE option in terms of GJ per functional unit (1 tonne of LDPE granulates produced in virgin-grade quality). In total, the result for the pyrolysis option is 38% better than for the virgin PE option.

The process emission of the pyrolysis system is 38% lower compared to the virgin PE production. The dominating effect in the pyrolysis system are the burdens due to energy recovery. Nevertheless, the overall result for resource use is significantly lower in the pyrolysis option.

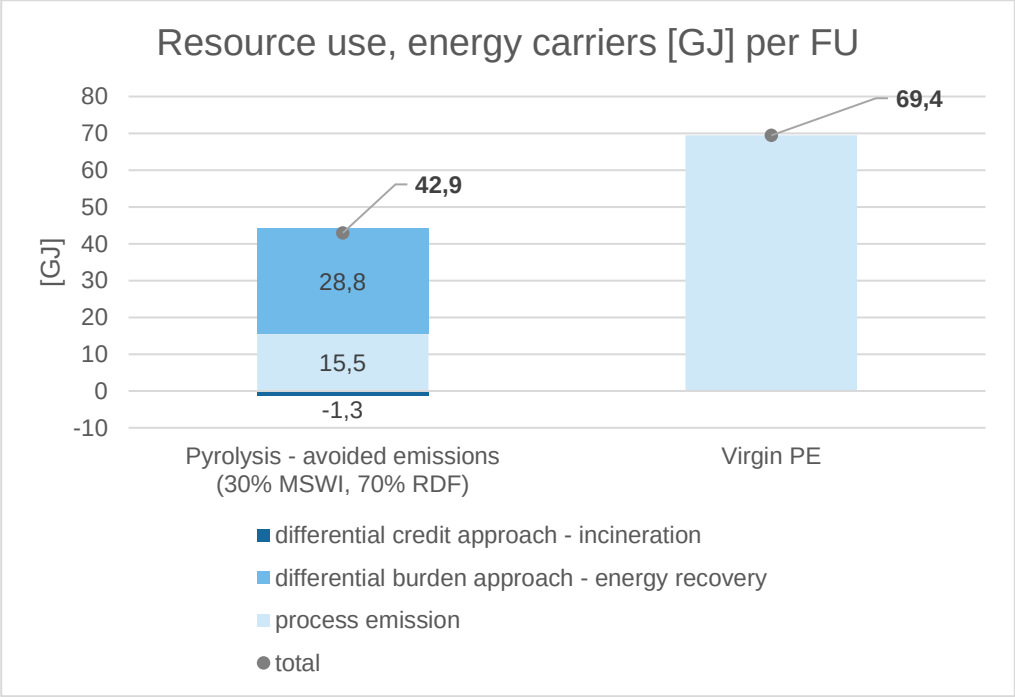


Figure 3-5 EF 2.0 Resource use, energy carriers [GJ] per FU – case study #2

Analysis:

In the pyrolysis systems natural gas, as non-renewable resources, is dominating the total resource use result.

The figure above shows that differential burden approach – energy recovery is the dominant contributor. The contribution analysis shows that 66% of the impact comes from the thermal energy credits, mainly due to the thermal energy from natural gas; and 44% from the electricity credits.

The second most important contribution comes from process emissions. The contribution analysis shows that 37% of the impact is from the purification process, of which the main contributor is the consumption of sodium methylate. 24% of the impact comes from the pyrolysis process, 17% of the impact from the cracker process and 21% from the polymerization process. The waste collection and sorting, extra sorting and transportation process have a negative resource use of -1,3 GJ. per functional unit, mainly because of the thermal treatment of losses in the extra sorting step.

Overview of selected impact categories:

The following graphics give an overview on all selected impact categories for the assessed systems.

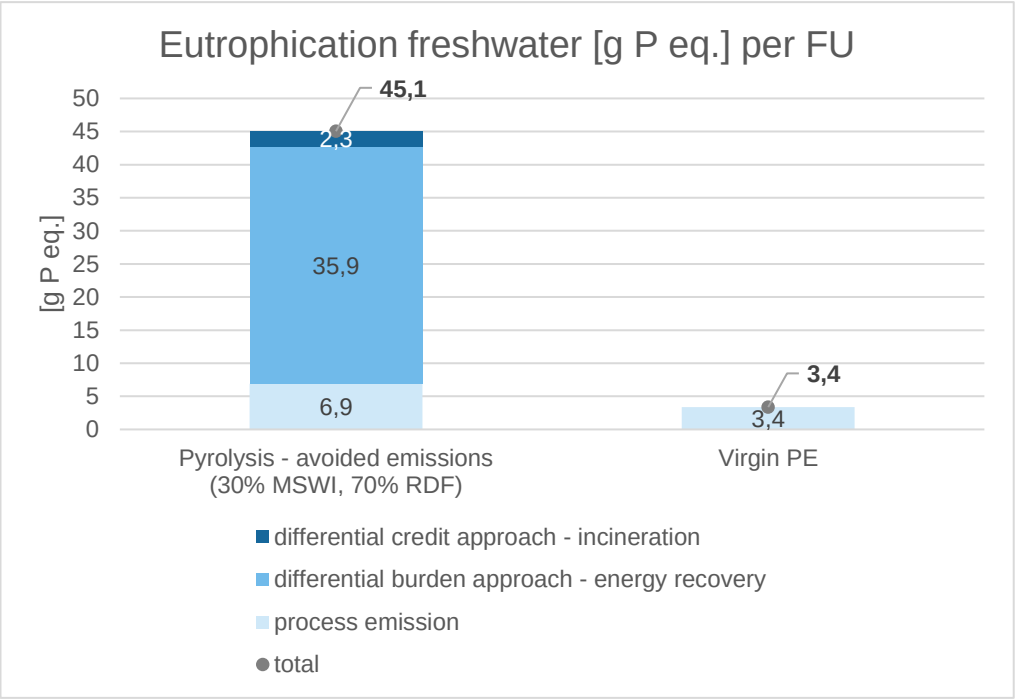


Figure 3-6 EF 2.0 Eutrophication freshwater [g P eq.] per FU – case study #2

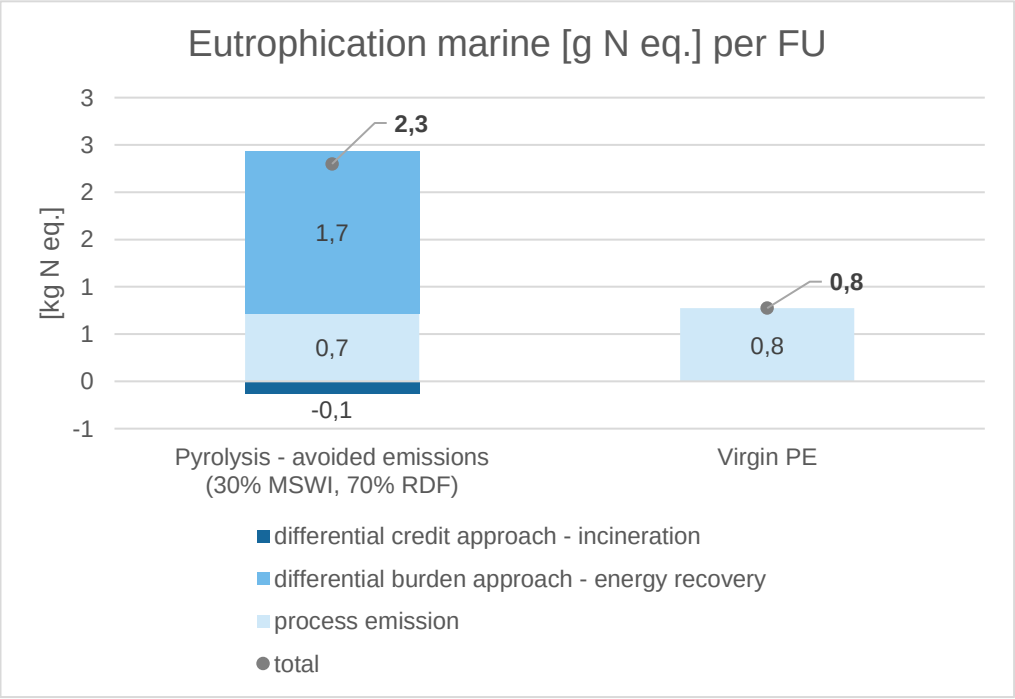


Figure 3-7 EF 2.0 Eutrophication marine [g N eq.] per FU – case study #2

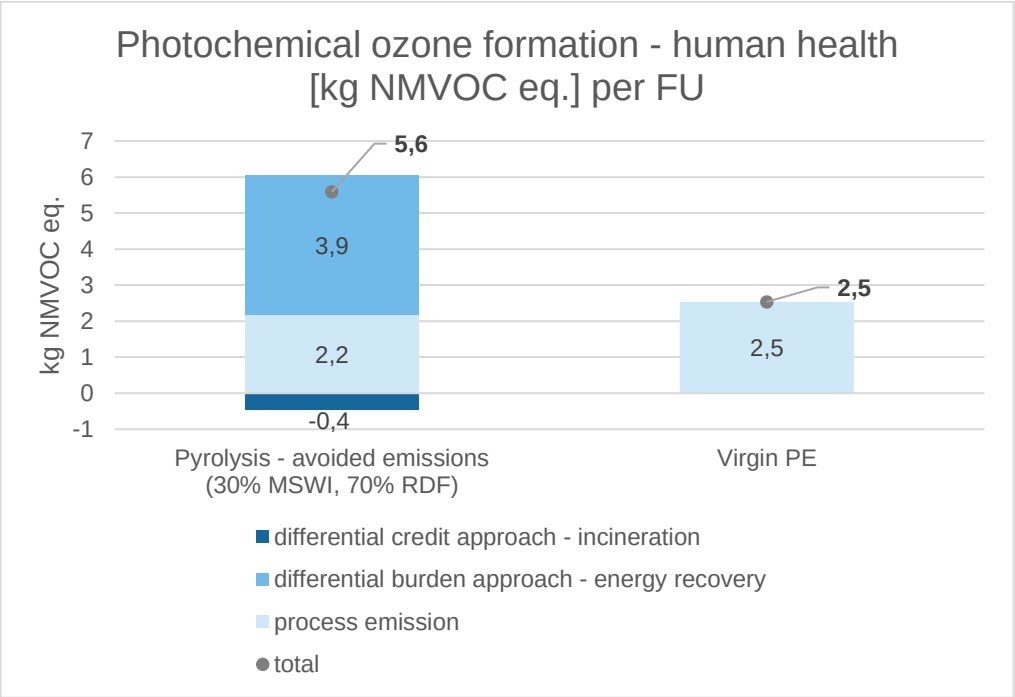


Figure 3-8 EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.] per FU – case study #2

Analysis:

The results for eutrophication freshwater, eutrophication marine and photochemical ozone formation - human health are trend- and content-wise comparable to the results for acidification terrestrial and freshwater. For all these impacts, the virgin PE option is showing significantly better results than the pyrolysis option. The differential burden approach – energy recovery is the dominant contributor, mainly due to the thermal energy credits from biogas and natural gas. The second most important contributor is the process emissions, mainly from the electricity consumption in the pyrolysis process and the ethylene production.

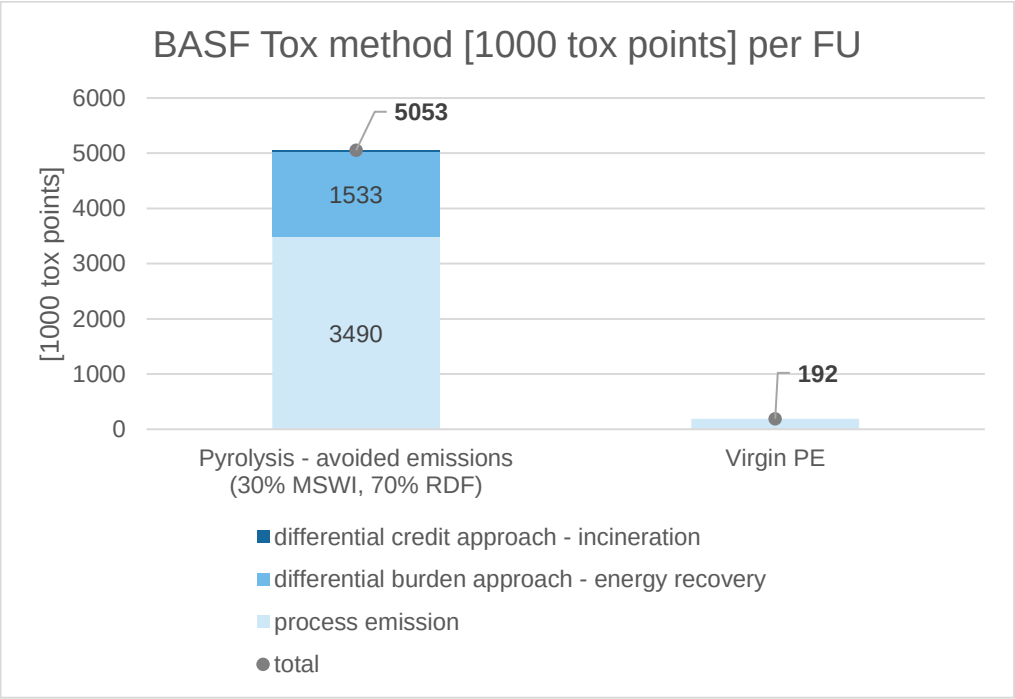


Figure 3-9 BASF Tox method [1000 Tox point] per FU – case study #2

Analysis:

Toxicity results are driven by the process emissions, mainly due to the ethylene production and the differential burden approach – energy recovery, mainly due to electricity credits

Analysis of ReCiPe indicators in comparison to assessed impact categories

The ReCiPe indicator results are shown in Annex A. When comparing the assessed categories from Table 2-8 with the ReCiPe indicators, the same general trends are observed with the exception of some toxicity indicators. The "human toxicity - non cancer" indicator in ReCiPe follows the same trend as the BASF toxicity method. However, the MSWI system has better results for the indicator "human toxicity – cancer" compared to the pyrolysis system. The EF2.0 indicators for human health effects have opposite trends compared to ReCiPe. "Cancer human health effects" follows the same trend as BASF human toxicity whereas "non-cancer human health effects" do not. At present, toxicity methods in LCA do not deliver robust results and therefore those results can certainly give additional information for the interpretation of results but should be handled with care in context of drawing conclusions.

Please consider also the effect on the total results of the selected indicators when applying different energy credits as described in the end of section 2.4.1.

3.4.2. Scenario Analysis

Strategies on cutting greenhouse gas emissions which are aiming on short- and long-term targets have been defined by the European Commission (https://ec.europa.eu/clima/policies/strategies_en). Climate Change is therefore a key performance indicator in the waste-to-energy and chemical sectors which is extensively discussed within the group of external and internal stakeholders defined as the intended audience of this study due to the challenges around climate change. As a consequence, the scenarios are analysed for the result indicator climate change based on CO_2-eq only.

Scenario group 1: Technologies considered in the product systems due to system expansion:

For a description of this scenario group, please see section 3.2.4.

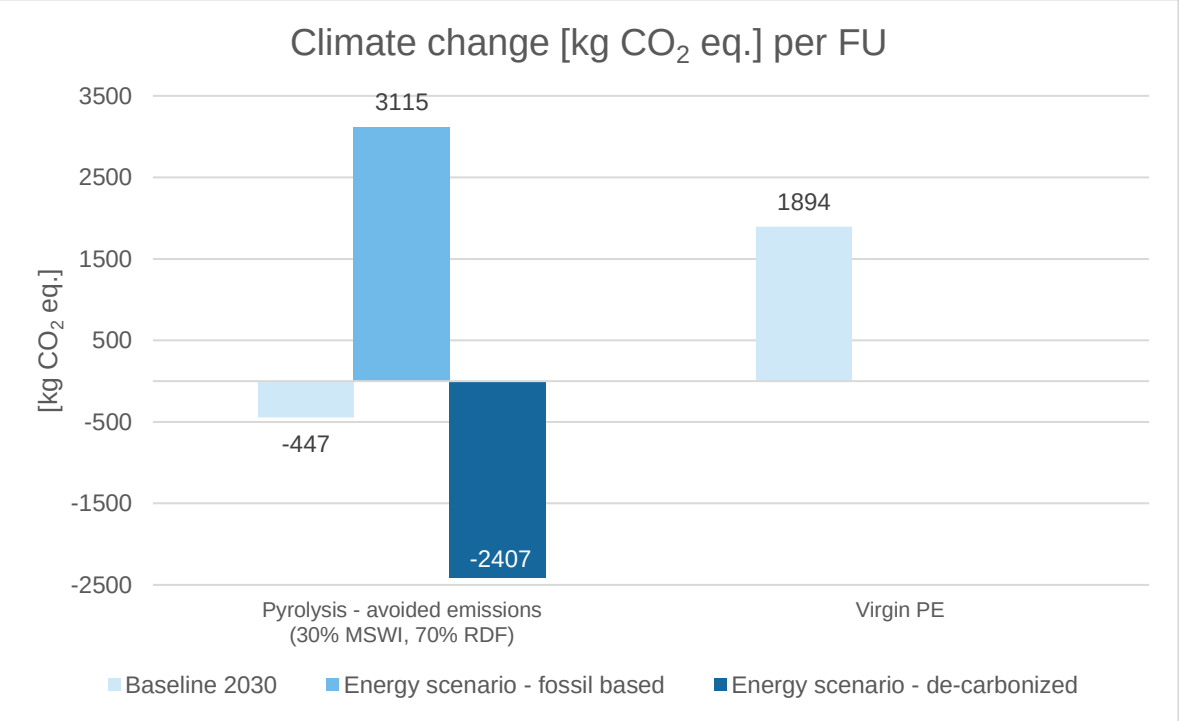


Figure 3-10 Scenario group 1 – case study #2 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

This scenario is used to derive potential LCA results of the assessed systems both in relation to other European countries besides Germany and the future beyond 2040, with >20 years considered as "mid-term" related to sectoral developments.

The range of climate change results for the pyrolysis system is very large considering the extreme cases for the energy credits. The energy credits act in the pyrolysis system as burdens. The fossil-based scenario has significantly worse climate change results than basic system. This scenario might be representative for parts of Eastern Europe. The de-carbonized energy credit scenario could represent the mid-term future for some European countries (e.g. Scandinavian countries), so in the year 2040 and beyond. The climate change results for the pyrolysis system in 2030 suffer from partly fossil-based energies. In the future as de-carbonization of the industry is the mid-term goal for Germany and other European countries, the pyrolysis system significantly benefits in terms of climate change results from the energy credits.

Thus, the trend in comparison of both systems is significantly affected by the energy recovery burdens due to incineration in the pyrolysis system which is prevented.

Scenario group 2: Target feedstock - extra effort in the extra sorting step

For a description of this scenario group, please see section 3.2.4.

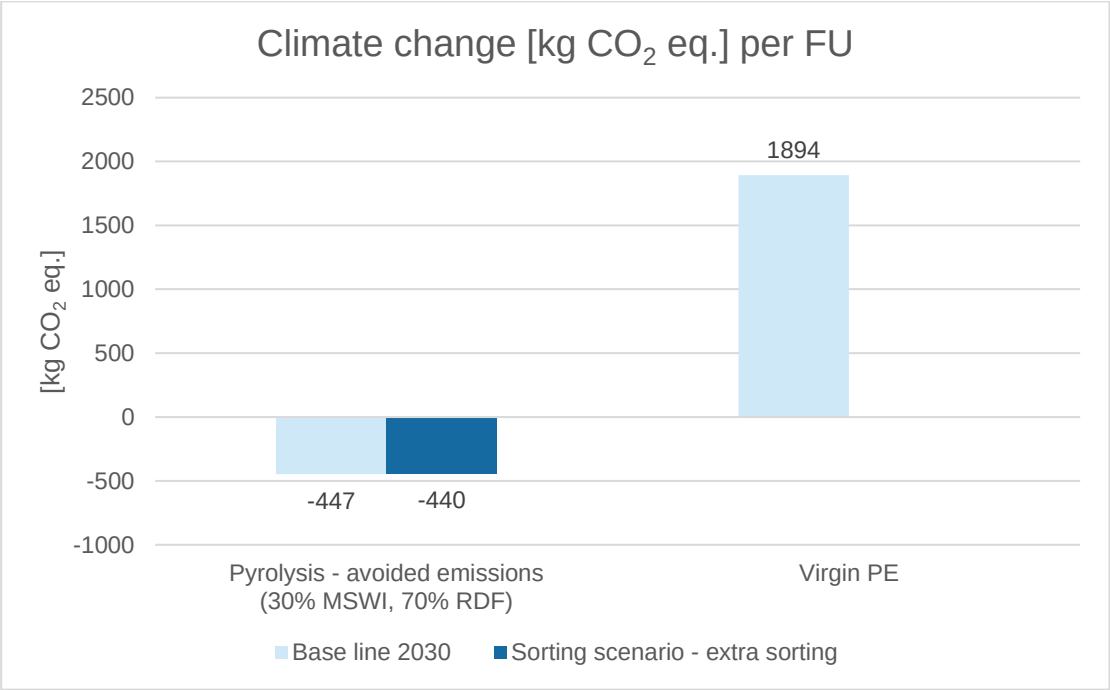


Figure 3-11 Scenario group 2 – case study #2 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

The higher energy consumption for the extra sorting of MPW in the pyrolysis system has a negligible effect to the total climate change results. As the overall results have shown in the previous section, the contribution of waste collection, sorting, extra sorting and transportation is below 2% of the climate change result regarding the “process emissions”.

Scenario group 3: Virgin production of LDPE in 2030

Base case for virgin production: industry-average data based on 2018 applied.

This scenario is not calculated using a prediction of the future virgin PE production. But it is obvious, that even if this production improves by 50% - which is highly unlikely - the trend of the total climate change result in comparison of the pyrolysis system including incineration which is prevented is not affected.

4. Case study #3 – product perspective - various qualities of plastic products

4.1. Goal of the Study

Reasons for carrying out the study

General reasons for carrying out the study that are applicable for all three case studies are described in section 1.3.

As the third part of the study "Evaluation of pyrolysis with LCA", case study #3, like case study #2, occupies the product perspective. The difference compared to case study #2 is the quality level of the assessed plastic products. Whereas case study #2 focuses on the production of an exemplary virgin-grade plastic (LDPE), case study #3 covers plastic products with a lower quality level than virgin-grade.

The goal of case study #3 is to evaluate the environmental impacts of pyrolysis - compared with alternative EoL technologies - as part of the life cycle of a mix of commodity plastics. PE, PP and PS granulates have been selected as the commodity plastics. Various quality levels of the recycled plastic products in the EoL have been considered using a cradle-to-grave LCA method including different quality levels of secondary materials that are politically accepted in Europe. As such, the Circular Footprint Formula (CFF) from the European PEF initiative has been used for this case study.

The baseline for the evaluation is the anticipated situation in 2030 in Germany.

The technical routes for production and end of life of commodity plastics considering various quality levels in EoL nowadays, and anticipated to be still be the case in 10 years in Germany, are (for selection of comparative system):

For plastic production (mix of commodity plastics)

- Virgin plastic production – results in virgin-grade plastic

- For plastic end of life (mix of commodity plastics)
  - thermal treatment in municipal solid waste incineration plants (= "waste-to-energy"),
  - application in cement kilns as alternative fuel,
  - mechanical recycling to produce plastic recyclate.

The majority of mixed plastic waste is currently incinerated either in MSWI or RDF plants (Umweltbundesamt, Analyse der Effizienz und Vorschläge zur Optimierung von Sammelsystemen der haushaltsnahen Erfassung von Leichtverpackungen und stoffgleichen Nichtverpackungen auf der Grundlage vorhandener Daten, Texte 37/2018, Mai 2018).

The cement kiln was assessed in case study #1 for different scenarios. To reduce the complexity of case study #3, the cement kiln has not been assessed.

Currently, mechanical recycling is one of the most important technologies for material recovery in the chemical sector and this is also expected to be the case in 2030. Mechanical recycling is used in case study #3 as the recycling method for mixed commodity plastic waste. Mechanical recycling as part of the end of life phase produces secondary granulate according to the share of commodity plastics in the production phase. These recyclates can have various quality levels and generally

have a reduced quality level compared to virgin-grade plastic due to impurities that are not completely removed during the cleaning stages of the recycling process. The rationale for the reduction in quality level related to recyclates in the context of case study #3 is twofold: mechanical recycling provides excellent products with mono-plastic waste as feedstock, but reduced quality with mixed plastic waste as feedstock. And the benchmark is food-grade packaging (=virgin grade) made of mainly polyolefins – especially mechanical attributes worsen at mechanical recycling of polyolefins.

Pyrolysis as part of the end of life phase produces virgin-grade LDPE granulate based on the mass balance principle as the exemplary plastic product.

Scenarios have been assessed to examine the influence on the overall results of predictable variations of developments compared to the baseline situation in the considered technologies. These scenarios have also been used to derive potential LCA results of the assessed systems in the context of other European countries than Germany and to points even further in the future, up to an anticipated situation in 2050.

Intended audience

The intended audience of the study are internal and external stakeholders in Europe regarding waste management, plastic waste treatment and circular economy in the chemical industry.

Intended application

The intended application of the study is to enrich the discussion about environmental evaluation of pyrolysis in the context of plastic waste recycling with respect to the end of life of plastic products with LCA-based data and results.

The results are intended to support comparative assertions and intended to be disclosed to the public. The study has been conducted according to the requirements of ISO 14040 (ISO 14040, 2006) and 14044 (ISO 14044, 2006). The requirements of (ISO/TS 14071, 2014) are respected.

4.2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

4.2.1. System boundaries, Product Systems, Product Function(s) and Functional Unit

The function of the product system is the production and end of life treatment of a mix of three commodity plastics (PE, PP, PS) in 2030 in Germany. The use phase is omitted since an application case for the commodity plastic granulates has not been defined.

One selected production technology for the virgin-grade commodity plastics and three selected EoL technologies are assessed. The functional unit is defined as *1 tonne of commodity plastic mix produced and treated* (the reference flow is the same as the functional unit).

The function and functional unit are consistent with the defined goal of the study.

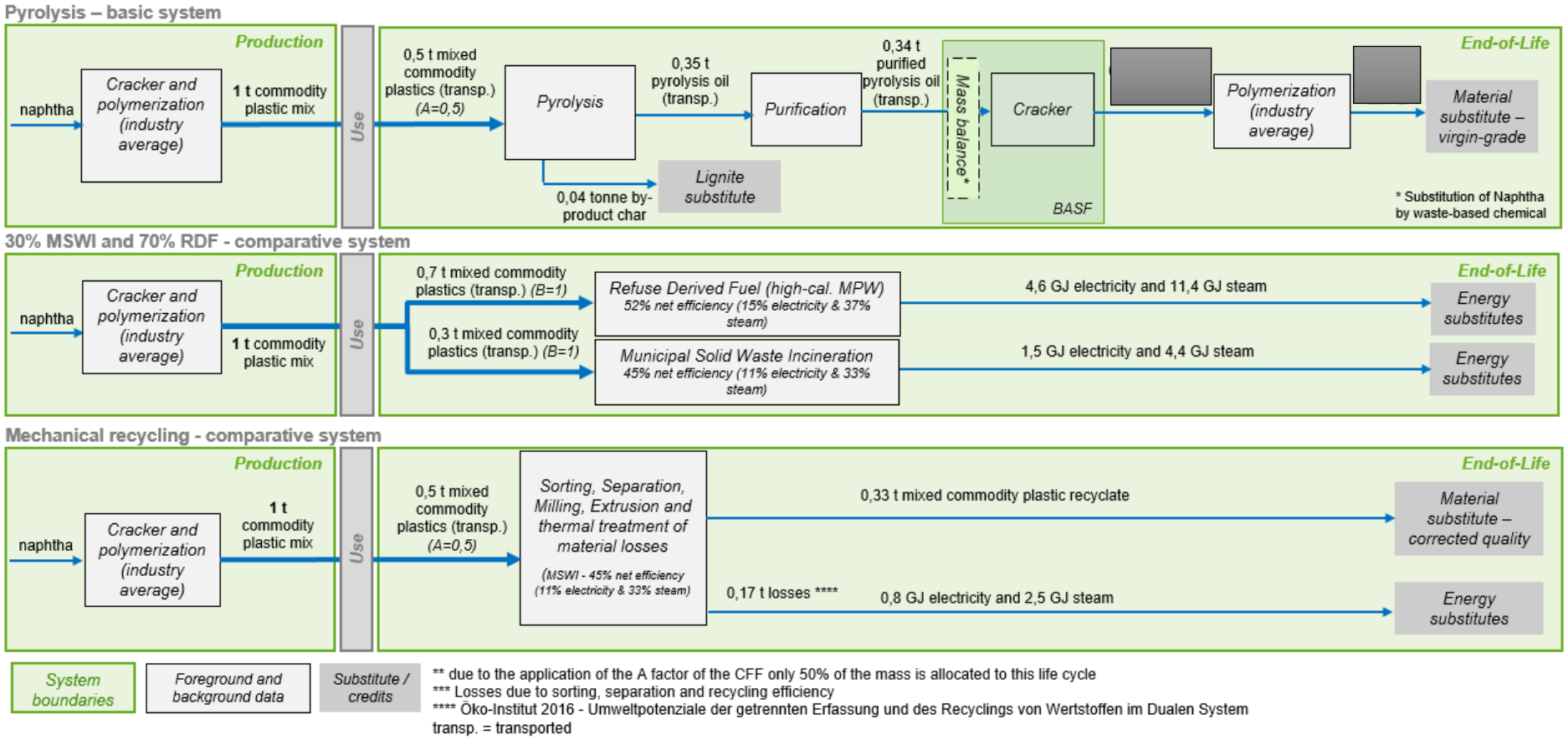


Figure 4-1: System boundaries – case study #3

The system boundaries of the basic and comparative systems are shown in Figure 4-1. The complete system, including the system expansion due to material and energy substitution, is displayed. Whenever transportation of materials or intermediates takes place, this is indicated next to the substance name in the system boundaries ("transp."). The type of transportation and assumed distances are described in the Life Cycle Inventory Analysis section (section 2.3).

As the production phase provides (after the omitted use phase) a mix of commodity plastic waste, mixed waste collection, mixed waste sorting to receive mixed plastic waste and extra sorting as in the case studies #1+#2 is not required and therefore not considered. The transports of the mixed plastic wastes to the respective EoL technologies is considered though.

Inclusions and exclusions are summarised in Table 4-2. No data were available for the elements of the systems that are excluded. However, it is assumed that the contributions to the overall results of case study #3 of the exclusions are minor.

Table 4-1 System boundaries – case study#3

Included		Excluded	
✓	Virgin production of commodity plastic mix	×	Capital goods
✓	MPW transport to pyrolysis plant, MSWI plant or mechanical recycling plant	×	Infrastructure
✓	MSWI technology with energy recovery (high-calorific waste)	×	Employee commute
✓	Pyrolysis technology with 1 main product and 1 by-product	×	Any administrative activities
✓	Transport of pyrolysis oil to purification	×	Use phase
✓	Purification of pyrolysis oil		
✓	BASF steam cracking		
✓	Polymerization of ethylene to LDPE		
✓	Mechanical recycling		
✓	Energy/fuel substitution of lignite, electricity and thermal energy		
✓	Material substitution for virgin-grade LDPE		
✓	Material substitution for lower quality level of recyclate		

Production of capital equipment, infrastructure and impacts associated with employee commuting and administrative activities have been excluded as these should not be relevant when allocated to the quantities of waste being processed.

No data were available for the baling press but this is likely to be insignificant compared other emissions from waste processing via either the base case or comparative scenario. In any case, this process would be applied to waste input to both assessed disposal routes and so does not introduce bias into the study.

The basic system and comparative system are equivalent in the following aspects:

- in the amount and type of product – commodity plastics,
- in the system boundaries applied: production and end of life of commodity plastics, and
- in the foreground and background data applied.

No functions associated with the different systems have been knowingly omitted from the study.

Table 4-2: Systems of case study #3

Case 3 - System	Short description
Basic system	*Production*: A mix of virgin-grade commodity plastics is produced (PE, PP, PS) based on virgin material (naphtha). *End-of-Life*: High-calorific value mixed plastic waste (PE, PP, PS) is treated in pyrolysis process. The resulting pyrolysis oil undergoes a purification step after which it is used as feedstock to produce virgin-grade plastic granulate. Virgin-grade LDPE is selected as exemplary chemical product for material substitution.
Comparative system 1	*Production*: A mix of virgin-grade commodity plastics is produced (PE, PP, PS) based on virgin material (naphtha). *End-of-Life*: High-calorific value mixed plastic waste (PE, PP, PS) is treated in an incineration plant, a combination of 30% MSWI and 70% RDF is used. The resulting energy (mix of thermal energy and electricity) is recovered and substitutes for thermal energy and electricity in the German market.
Comparative system 2	*Production*: A mix of virgin-grade commodity plastics is produced (PE, PP, PS) based on virgin material (naphtha). *End-of-Life*: High-calorific value mixed plastic waste (PE, PP, PS) is used as feedstock for mechanical recycling. Secondary granulates are produced that have various quality levels (on average, with reduced quality compared to virgin-grade plastic). Residual amounts of sorted high-calorific MPW are incinerated in MSWI. The resulting energy (mix of thermal energy and electricity) is recovered and substitutes for thermal energy and electricity in the German market.

Parameter settings for application of CFF

The Circular Footprint Formula (CFF) developed by the Joint Research Centre (JRC) of the European Commission has been applied to calculate the environmental impacts over the life cycle of the selected chemical products, please see (European Commission, Product Environmental Footprint Category Rules (PEFCR) Guidance, Version 6.3, May 2018, 2018). For a detailed description of the method, the formula and the applied parameters, please see the referenced guidance document.

The parameters of the applied Circular Footprint Formula (CFF) are summarised in the table below. They are based on Annex C of the PEF guidance (European Commission, Annex C - CFF Default Parameters, March 2018, 2018). The A factor [0;1] allocates burdens and credits between two life cycles and aims to reflect market realities. A low A factor (0,2 - default value for e.g. metals, glass and paper) reflects a low offer and a high demand of recyclable materials – so, the product system focuses on the recyclability of the product at the end of life. A high A factor (0,8 – default value for e.g. textiles) reflects a high offer and a low demand of recyclable materials – so, the product system

focuses then on recycled content. The default value for the A factor regarding systems with plastic products is 0,5 in all assessed systems – that reflects an equilibrium between offer and demand.

The B factor [0;1] is applied as an allocation factor for energy recovery technologies. For benchmark calculations the parameter B shall be equal to 0 by default.

The Q ratios [0;1] are used to take the quality of in- and outgoing secondary materials into account. The ratios are based on the price /market value ratio of primary and secondary materials. The quality of the recyclable material is defined at the point of substitution.

The quality parameter for outgoing secondary material (Qsout) of the mechanical recycling system is set to 0,5. According to (Conversio Market & Strategy, 2019), the economic value of secondary granulates produced by mechanical recycling based on mixed plastic waste is in average about 50% of the economic value of virgin-grade plastics.

The quality parameter for outgoing secondary material (Qsout) of the pyrolysis system is set to 1 as virgin-grade PE is produced as the exemplary chemical product.

As no ingoing secondary material is considered in the systems, Qsin is set to 1.

Table 4-3 CFF – parameters used in the case study #3

	Virgin-grade plastics & chemical rec.	Virgin-grade plastics & 30% MSWI and 70% RDF	Virgin-grade plastics & mech. recycling
A	0,5	0,5	0,5
B	0	0	0
Qsin	1	1	1
Qsout	1	n/a	0,5

4.2.2. Description of the representativeness of the chosen products and systems

Definition of the baseline systems – situation in 2030 in Germany

The technical development from now until 2030 of the assessed technologies has been considered. The following sections describe how this has been implemented in the case study to define the baseline in 2030.

Core technologies considered in the product systems:

For the pyrolysis technology, the purification technology and the MSWI technology – please see section 2.2.2.

For the steam cracker process at BASF and virgin plastic production – please see section 3.2.2.

Mechanical recycling is defined as the processing of plastic waste into secondary raw materials or products without significantly changing the chemical structure of the material, see (ISO 15270, 2008). The data used in this study are based on expert estimations that are considered to also be applicable for the year 2030. The environmental impacts of the estimated data for plastic recyclates have been compared to publicly available results - (APR (The Association of Plastic Recyclers), 2018). The CO_2 equivalents (climate change) for plastic recyclates based on the estimations applied in this study are comparable to the published study results for recycled PP and PE-HD.

Technologies considered in the product systems due to system expansion

For the generation of electricity and thermal energy – please see section 2.2.2.

Further technologies as part of the systems

For transportation - please see section 2.2.2.

Definition of the baseline products – situation in 2030 in Germany

Description of selected plastic commodities – PE, PP and PS granulates

- PE, PP and PS are currently the most important plastics used for lightweight packaging. PET is not considered as it is not feasible for the pyrolysis process in this study due to its oxygen content. It is anticipated that this will also be the case in 2030. These plastic commodities have the highest contribution by mass-% in mixed plastic waste streams – high-calorific mixed plastic waste consists only of PE, PP and PS.
- According to a recent study on lightweight packaging waste in Germany (Institut cyclos-HTP, 2018), the share of plastic waste that can be used for material recovery is 32% of the lightweight packaging waste input (32% corresponds to 833.100 tonne per year). PE, PP and PS account for 92% of this waste fraction.
- The remaining shares of lightweight packaging waste are 16,8% of plastic waste which cannot be used for material recovery, tinplate 10,5%, aluminium and compounds with aluminium 3,6%, beverage cartons 6%, paper/cardboard and compounds with paper/cardboard 5,3% and others [1]25,8%.

Description of PE, PP and PS recyclate

- Secondary products from mechanical recycling can have various quality levels and many different application cases – in this respect, it is assumed that the situation in 2030 will be the same as it is today.

Description of selected exemplary chemical product – virgin-grade LDPE

Please see section 3.2.2

[1] Others: mainly plastic waste, but not belonging to the faction “lightweight packaging waste”

4.2.3. Key performance characteristics

For characteristics of mixed plastic waste (MPW), high-calorific mixed plastic waste, (residual) municipal waste and purified pyrolysis oil – please see section 2.2.3.

Virgin-grade plastic granulates - with focus on possible application as packaging material

For characteristics of virgin grade LDPE granulate – please see section 3.2.3. Key characteristics of polypropylene in food applications are listed below.

- Packaging applications: high strength, good surface finish.
    - Flexible packaging: PP films' good optical clarity and low moisture-vapor transmission make it suitable for use in food packaging.
    - Rigid packaging: PP is blow moulded to produce crates, bottles, and pots. PP thin walled containers are commonly used for food packaging.
    - PP film is among the leading materials today used for flexible packaging as well as industrial applications.

Commodity plastic granulates with various quality levels

The characteristics of PE, PP and PS recyclate vary as the quality level varies. No definite specifications and characteristics are available for secondary plastic granulates, so these have not been explicitly specified in this report. Examples for application cases give an overview on the range of different quality levels:

Consumer goods like toys, luggage, furniture - comparable to virgin-grade plastic:

- Park bench – material substitute for wood or concrete;
- Flower tub - material substitute for ceramics or wood;
- Secondary plastic blended with virgin-grade plastic in packaging automotive applications.

4.2.4. Scenario description

Scenario group 1: Technologies considered in the product systems due to system expansion

Scenario group 1 assesses the influence of national energy grid mixes, both for electricity and thermal energy, in terms of time coverage and geographical coverage within case study #1 with a link to European countries besides Germany and a link to "mid-term" future developments (> 20 years from now) on the energy market. It focuses on the recovered energies that are substituted and result in environmental credits in the system. Two extreme scenarios concerning CO_2-eq. emissions have been defined with energy produced conventionally from base load energy plants. One assesses the GHG impact on the comparative systems if the recovered energies and electricity are substituted with fossil energies and electricity, the other one with renewable (see Table 4-4).

Table 4-4 Case study #3, Scenario group 1 overview: Technologies considered in the product systems due to system expansion

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 1	× Pyrolysis ✓ 30% MSWI - 70% RDF × Mechanical recycling	**Base case**	Baseline 2030	Recovered energies and electricity substitute anticipated future energy and electricity mixes for Germany in 2030 (see tables 2-11 and 2-12).
		Scenario 1	Energy credit, fossil	Recovered electricity substitutes electricity from lignite. Recovered heat substitutes thermal energy from heavy fuel oil (HFO).
		Scenario 2	Energy credit, de-carbonized	Recovered electricity substitutes electricity from hydro power. Recovered heat substitutes thermal energy from renewable resources (biogas and biomass).

Scenario group 2: Parameter settings for application of CFF - Quality of recyclate

A further scenario analysis has been undertaken to examine the influence on the results of the recyclate quality. The recyclates' quality from the pyrolysis system does not vary as it is known to be of virgin grade quality based on mass balance principle. Table 4-5 shows an overview of the assessed scenarios with respect to the parameter Q_{sout} of the CFF.

Table 4-5 Case study #3, Scenario group 2 overview: Parameter settings for application of CFF – Quality of recyclate

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 2	× Pyrolysis × 30% MSWI - 70% RDF ✓ Mechanical recycling	**Base case**	Baseline 2030	Q_{sout} = 0,5. Multi-cycling of the material reduces the quality.
		Scenario 1	Q_{sout} = 1	Q_{sout} = 1. Recyclate has virgin-grade quality
		Scenario 2	Q_{sout} = 0,75	Q_{sout} = 0,75. Multi-cycling of the material reduces the quality.
		Scenario 3	Q_{sout} = 0,25	Q_{sout} = 0,25. Multi-cycling of the material reduces the quality (Alternative rationale: after 1 recycling round, the food-grade characteristics of the packaging material are lost).
		Scenario 4	Q_{sout} = 0	Q_{sout} = 0. Multi-cycling of the material causes an enrichment of substances that does not allow any further use regarding its technical performance. Further rationale: The food-grade characteristics of the packaging material are lost.

Scenario groups 3 & 4: Core technologies considered in the product systems: Mechanical recycling

Sensitivity analyses have been conducted to assess the influence of relevant parameters of the mechanical recycling process that are energy consumption and material efficiency.

As secondary data are used for the mechanical recycling, a scenario analyses the GHG results if the energy inputs are varied by ±30% (Table 4-6). Base case for energy consumption in mechanical recycling is modelled as 1,3 MJ electricity per kg input.

Table 4-6 Case study #3, Scenario group 3 overview: Core technologies considered in the product systems: energy efficiency of mechanical recycling

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 3	× Pyrolysis × 30% MSWI - 70% RDF ✓ Mechanical recycling	**Base case**	Baseline 2030	1,3 MJ electricity input per 1 kg plastic input.
		Scenario 1	+30% energy consumption	The energy input is varied by +30%.
		Scenario 2	-30% energy consumption	The energy input is varied by -30%.

Another scenario considers a variation in material losses in the mechanical recycling as the data are not based on primary sources. The material efficiency in the base case is 66,5% (see section 4.3.3, reference: (Dehoust, 2016)). The scenario analyses a decreased material efficiency of 46% based on data as well from (Dehoust, 2016) and an increased material efficiency of 90% based on confidential information from mechanical recycling expert (Table 4-7). The results from scenario group 4 are shown in combination with the results of scenario group 2.

Table 4-7 Case study #3, Scenario group 4 overview: Core technologies considered in the product systems: Mechanical recycling –material efficiency & quality of recyclates

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 4	× Pyrolysis × 30% MSWI - 70% RDF ✓ Mechanical recycling	**Base case**	Baseline 2030	0,345 kg losses per kg plastic input (66,5% efficiency). Qsout = 0 – 1 (full range of potential product qualities)
		Scenario 1	Decreased material efficiency	0,54 kg losses per kg plastic input (46% efficiency) Qsout = 0 – 1 (full range of potential product qualities)
		Scenario 2	Increased material efficiency	0,1 kg losses per kg plastic input (90% efficiency) Qsout = 0 – 1 (full range of potential product qualities)

Scenario groups 5 & 6: Parameter settings for application of CFF

Both parameters of the Circular Footprint Formula (CFF) are based on political decisions in the development process of the CFF. A scenario analysis in scenario group 4 has been undertaken to examine the influence on the results of varying the values for the parameters A and B in the CFF calculation.

The default values result in halved burdens and credits for material recovery of plastics (A=0,5), but full burdens and credits for energy recovery (B=0).

Two extreme methodological scenarios are testes. One (Table 4-8) resulting in full material burdens and credits (A=0) in combination with halved burdens and credits for energy recovery (B=0,5). The other one (Table 4-9) resulting in no material burdens and credits (A=1 /cut-off approach) in combination with halved burdens and credits for energy recovery (B=0,5).

Table 4-8 Case study #3, Scenario group 5 overview: Parameter settings for application of CFF – A=0; B=0,5

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 5	✓ Pyrolysis × 30% MSWI - 70% RDF ✓ Mechanical recycling	**Base case**	Baseline 2030	CFF parameters set to A=0,5 and B=0
		Scenario	CFF: A=0; B=0,5	CFF parameters set to A=0 and B=0,5

Table 4-9 Case study #3, Scenario group 6 overview: Parameter settings for application of CFF – A=1; B=0,5

Scenario group	Affected systems	Scenario	Scenario name	Description
Scenario group 6	✓ Pyrolysis × 30% MSWI - 70% RDF ✓ Mechanical recycling	**Base case**	Baseline 2030	CFF parameters set to A=0,5 and B=0
		Scenario	CFF: A=1; B=0,5	CFF parameters set to A=1 and B=0,5

4.2.5. Time Coverage

The intended time reference is the year 2030. All elements in the assessed baseline systems are adapted as good as possible to this time reference as described in section 2.2.2 and 3.2.2.

The scenarios partly prolong the time coverage to at least 2040.

4.2.6. Technology Coverage

The intended technology references cover the production and EoL of virgin-grade and secondary commodity plastics in Germany in the year 2030:

- Virgin and secondary production of commodity plastics
- Pyrolysis (pyrolysis with MPW as feedstock and purification) combined with cracking and polymerization processes
- Waste-to-energy (MSWI and RDF)
- Mechanical recycling

Further technologies are covered in case study #3 which are linked to those core technologies:

- Generation of electricity in 2030 based on 100% fossil energy resources and 100% renewable energy resources
- Generation of thermal energy in 2030 based on 100% fossil energy resources and 100% renewable energy resources

4.2.7. Geographical Coverage

The intended geographical reference is Germany.

The scenarios extend the geographical coverage to European countries besides Germany.

4.2.8. Allocation

For multi-output allocation and End-of-Life allocation – please see section 2.2.8

Mass Balance

The concept of “mass balance” as described in Jeswani et al. (2019) is applied for the ethylene production (BASF steam cracker). The cracker input material naphtha is substituted by purified pyrolysis oil based on the lower heating value.

CFF

The allocation rules are applied as described in (European Commission, Product Environmental Footprint Category Rules (PEFCR) Guidance, Version 6.3, May 2018, 2018).

4.2.9. Cut-off Criteria

No cut-off criteria are defined for this study. As summarized in section 0, 3.2.3 and 4.2.3, the system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The influence of these proxy data on the results of the assessment is discussed in Chapter 5.

4.2.10. Selection of LCIA Methodology and Impact Categories

Please see section 2.2.10.

4.2.11. Interpretation to Be Used

Please see section 2.2.11.

4.2.12. Data Quality Requirements

Please see section 2.2.12.

4.2.13. Type and format of the report

Please see section 2.2.13.

4.2.14. Software and Database

Please see section 2.2.14.

4.2.15. Critical Review

Please see section 2.2.15.

4.3. Life Cycle Inventory Analysis

4.3.1. Data Collection Procedure

Please see section 2.3.1.

4.3.2. Commodity plastics

Commodity plastics are used as representatives for high-end application cases. A mix of virgin commodity plastics (PE, PP, PS) based on virgin material (naphtha) is used in the model. The share of commodity plastics is based on the composition in the yellow bag, see Annex C. Databases for PE, PP and PS are from the GaBi 2018 database. Documentation for all GaBi datasets can be found online (Sphera, 2019).

4.3.3. Foreground System

Chemical Recycling – Pyrolysis

Please see section 2.3.2.

Cracking

Please see section 2.3.2.

Polymerization

Please see section 2.3.2.

Municipal Solid Waste Incineration

Please see section 2.3.2.

Mechanical recycling

Mechanical recycling consists of two main steps: pre-treatment of plastic waste and production of recycled plastic granulate. The pre-treatment step includes e.g. sorting, grinding, washing and drying. The production of recycled plastic comprises the separation of materials, removal of contaminants, additional sorting, extruding and finally the pelletising.

In the foreground system, secondary data for the mechanical recycling has been used. The total energy demand is shown in Table 4-10 (Dehoust, 2016). Material recovery efficiency is assumed to be 66,5% - losses occur due to sorting and separation. This is considered to be a conservative approach as this is the fraction of mixed plastic waste with the highest material recovery efficiency documented in Dehoust (2016). Waste from the process is treated in a waste incineration plant with energy recovery. System expansion has been used to account for the benefits of steam and electricity produced in the incineration plant. In the foreground system, secondary data from the GaBi databases for fuels and auxiliaries have been used, these databases are representative for the technologies applied and the geographical region.

Table 4-10 Unit process data for mechanical recycling

Type	Flow	Value	Unit	DQI*
Inputs	Electricity	1,89	MJ	Literature
	Plastic waste	1,50	kg	Literature
Outputs	Plastic granulate	1,0	kg	Literature
	Material losses	0,50	kg	Literature

4.3.4. Background System

Documentation for all GaBi datasets can be found online (Sphera, 2019).

Fuels and Energy

Please see section 2.3.2.

Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2018 database. Table 4-11 shows the most relevant LCI datasets used in modelling the product systems.

Table 4-11 Key material and process datasets used in inventory analysis – case study #3

Location	Dataset	Data Provider	Reference Year	Proxy?
DE	Waste incineration (municipal waste)	Sphera	2018	no
DE	Nitrogen allocated by volume	BASF	2018	no
DE	Compressed air	BASF	2018	no
DE	Hydrogen 25 bar	BASF	2018	no
DE	Sodium methylate, 30% solution in Methanol	BASF	2018	no
DE	Tap water from groundwater	Sphera	2018	no
DE	Demineralized Water LU (Water 0% consumptive)	BASF	2018	no
DE	Municipal wastewater treatment (mix)	Sphera	2018	no
DE	Lignite mix	Sphera	2016	no
DE	Naphtha at refinery	Sphera	2016	no
DE	Nitrogen via cryogenic air separation production mix, at plant liquid	Sphera	2018	no
DE	Residues	BASF	2018	no
DE	Cooling water from river	BASF	2018	no
DE	Natural gas mix	Sphera	2016	no
DE	Sodium hydroxide	BASF	2018	no
DE	Polyethylene Low Density Granulate (LDPE/PE-LD)	Sphera	2018	no

Location	Dataset	Data Provider	Reference Year	Proxy?
DE	Polystyrene granulate (PS)	Sphera	2018	no
DE	Polypropylene granulate (PP)	Sphera	2018	no
DE	Polyethylene Low Density Granulate – polymerization process	Sphera	2018	no

Transportation

Please see section 2.3.2.

4.3.5. Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the "outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment". As the complete inventory comprises hundreds of flows, the below table only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results.

Table 4-12: LCI results of case study #3*

Flow	Unit	Virgin commodity plastics & pyrolysis	High quality commodity plastics & (30% MSWI, 70% RDF)	Virgin commodity plastics & mechanical recycling
Resources				
Carbon dioxide**	kg	125,7	-940,8	-46,1
Energy resources				
Crude oil (in MJ)	MJ	26.578,7	33.812,0	29910,9
Hard coal (in MJ)	MJ	1.887,7	239,8	1411,9
Lignite (in MJ)	MJ	1.250,4	770,9	1627,4
Natural gas (in MJ)	MJ	23.106,9	16.971,5	21965,8
Uranium natural (in MJ)	MJ	892,1	1.377,2	1130,7
Emissions				
Inorganic emissions to air				
Ammonia	g	24,6	-9,1	19,2
Carbon dioxide	kg	1.891,2	3.481,0	1761,2
Carbon dioxide (biotic)	kg	133,3	-934,0	-43,4
Carbon dioxide (land use change)	kg	1,5	-10,0	-0,4
Carbon monoxide	g	848,8	-142,6	688,1
Nitrogen dioxide	g	1,8	-0,7	1,0
Nitrogen monoxide	g	10,1	-42,5	0,5
Nitrogen oxides	g	1.717,1	193,4	1383,3
Nitrous oxide (laughing gas)	g	40,4	-70,0	22,4
Sulphur dioxide	kg	1,1	0,4	1,0

Organic emissions to air (group VOC)				
Butane (n-butane)	g	61,6	60,5	65,1
Ethane	kg	0,2	0,2	0,2
Formaldehyde (methanal)	g	5,0	-7,6	3,1
NMVOC (unspecified)	g	392,0	352,7	355,7
Pentane (n-pentane)	g	25,1	10,0	24,0
Propane	kg	0,3	0,3	0,3
Methane	kg	5,8	6,3	6,0
Methane (biotic)	kg	0,1	-0,9	0,0
VOC (unspecified)	g	303,5	0,0	0,0
Inorganic emissions to fresh water				
Ammonia	g	0,5	0,7	0,6
Chloride	kg	69,3	85,9	77,4
Nitrate	g	145,4	-918,8	-33,4
Nitrogen	g	0,0	-1,4	-0,1
Nitrogen (as total N)	g	0,9	0,0	0,0
Phosphate	g	7,2	-46,5	-1,3
Phosphorus	g	1,3	-2,9	0,2
Inorganic emissions to sea water				
Chloride	kg	19,9	25,2	22,3

* Negative values are due to the system expansion approach for the multioutput processes, please see section 2.2.8.
** Carbon dioxide (resource) has not been corrected in the LCIs of production systems.

4.4. LCIA Results

This chapter contains the results for the impact categories defined in section 2.2.10. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

4.4.1. Overall Results

The results in the graphs have been broken down to show the contribution to the total impacts from virgin commodity plastic production “production”; the end of life activities in all systems “EoL - process emissions”, such as transportation, incineration process, pyrolysis and purification steps, cracking, polymerization and mechanical recycling; and the credits associated to the energy and material substitutions “EoL - material/energy substitution”.

The analysis for the results focuses on pyrolysis and mechanical recycling as the MSWI system results are analysed in case study #1.

Results are influenced by the factors A and B in the CFF calculation. If the net effect in EoL is positive (net credit in EoL) in a system, then a low value for factor A and B (<0,5) is beneficial to the total results as the full credit is applied. A high value of factor A and B (>0,5) has an adverse effect on the total results as the credits are only partly considered. The opposite is true when the net effect in EoL is negative (net burden in EoL).

Whenever the term “significantly” is used, it refers to minimum differences in results of ±10%.

Climate Change

The overall results for climate change show that the pyrolysis and mechanical recycling technologies have significant advantages compared to the incineration technologies in terms of CO_2-equivalents per functional unit (1 tonne of commodity plastic mix produced and treated). There is no significant difference (about 7%) between chemical and mechanical recycling. Emissions for the commodity plastics production is the same for the three systems.

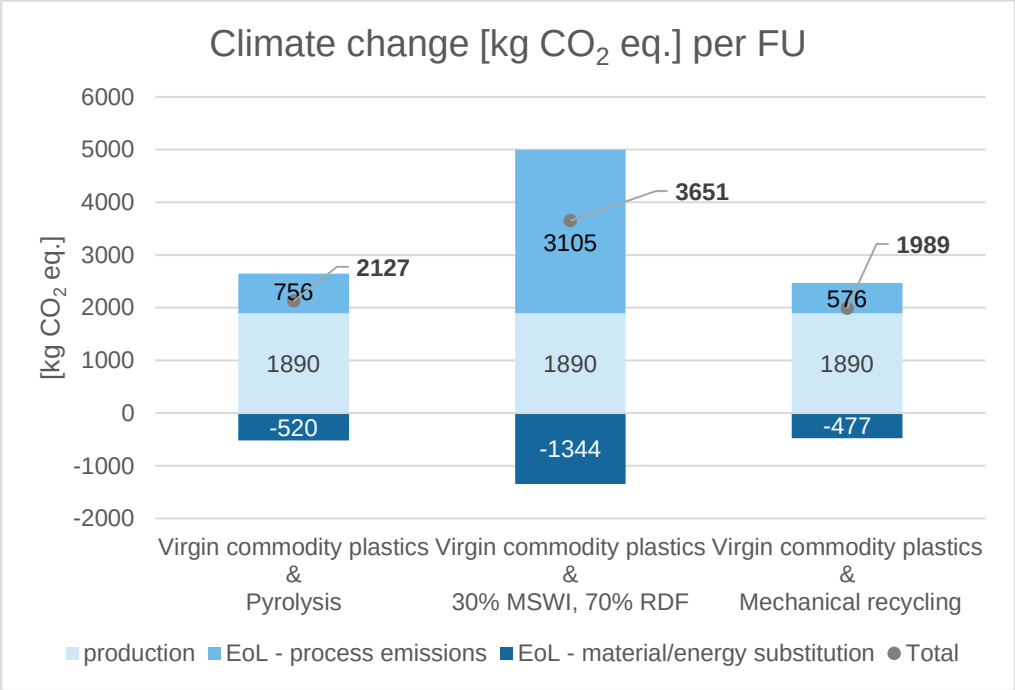


Figure 4-2 EF 2.0 Climate Change total [kg CO_2 eq.] per FU – case study #3

Analysis:

Climate change is driven by inorganic emissions to air, primarily carbon dioxide.

The figure above shows that the process emissions in the pyrolysis system account for 756 kg CO_2-eq. The contribution analysis shows that the pyrolysis process is the main contributor 56% (mainly due to direct CO_2 emissions from pyrolysis step), 24% of the impact comes from the cracker process 24%, 12% from the polymerization process and 7% from purification process.

The credit in the pyrolysis system is dominated by virgin-grade LDPE.

The process emissions in the mechanical recycling system account for 576 kg CO_2-eq. The contribution analysis shows that 90% of the impact is from the incineration of material losses and 10% from mechanical recycling (including transportation). The credit in the mechanical recycling system is 66% related to substitution of material and 33% to substitution of recovered energy.

Acidification

The overall results for acidification show that the incineration option has significant advantages compared to the chemical and mechanical recycling options in terms of Mole of H^+-equivalents per functional unit (1 tonne of commodity plastic mix produced and treated). There is no significant difference between chemical and mechanical recycling.

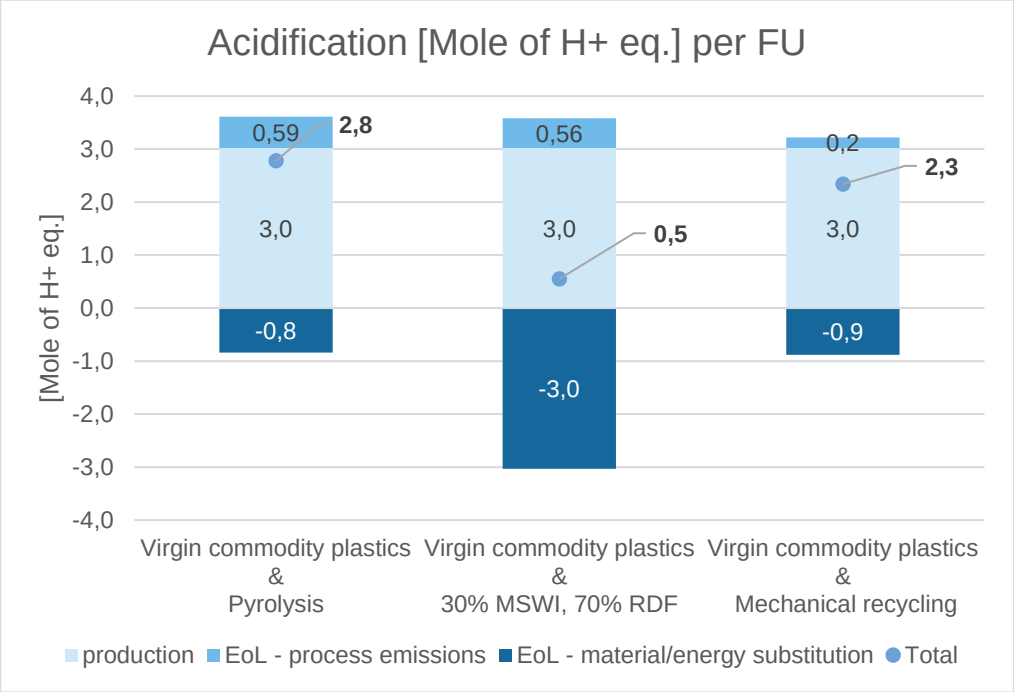


Figure 4-3 EF 2.0 Acidification terrestrial and freshwater [Mole of H^+ eq.] per FU – case study #3

Analysis:

In all systems, the SO_2 and NO_x emissions are the dominating contributors to the total Mole of H^+ equivalents.

The process emissions in the pyrolysis system account for 0,59 Mole of H^+ eq. The contribution analysis shows that 37% of the impact comes from the pyrolysis process (main contributor: consumption of electricity), 26% from the cracker process, 26% polymerization process and 12% from the purification process.

The credit in the pyrolysis system is dominated by virgin-grade LDPE.

The process emissions in the mechanical recycling system account for 0,2 Mole of H^+ eq. The contribution analysis shows that 54% of the impact is from the mechanical recycling (incl. transportation) and 46% from the incineration of material losses. The credit in the mechanical recycling system splits up to about 57% related to substitution of material and about 43% to substitution of recovered energies.

Resource use of energy carriers

The overall result for resource use of energy carriers shows that no option has significant advantages or disadvantages in terms of GJ per functional unit (1 tonne of commodity plastic mix produced and treated).

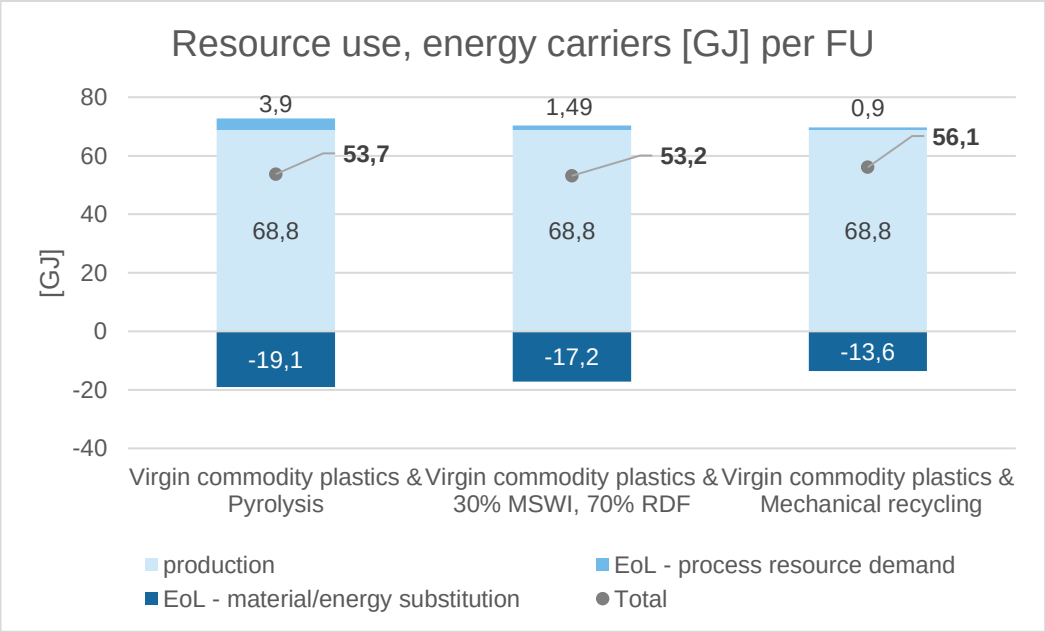


Figure 4-4 EF 2.0 Resource use, energy carriers [GJ] per FU – case study #3

Analysis:

No detailed analysis has been undertaken for the “EoL – process resource demand” in this section, as the contribution to the total results is not relevant in all systems.

The credit in the pyrolysis system is dominated by virgin-grade LDPE.

The credit in the mechanical recycling system splits up to about 84% related to substitution of material and about 16% to substitution of recovered energies.

Overview of selected impact categories:

The following table gives an overview of all selected impact categories for both assessed systems.

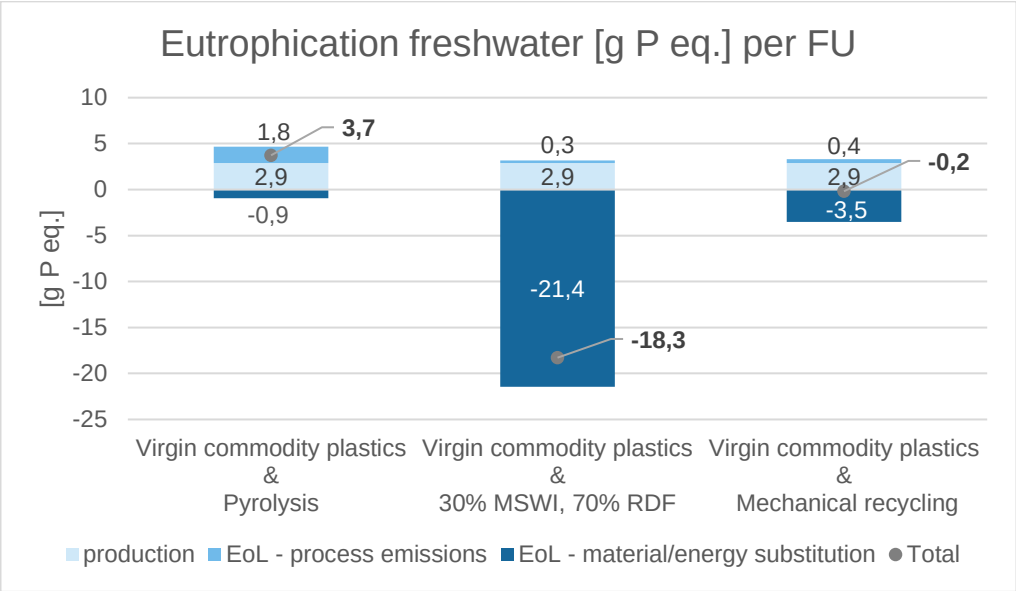


Figure 4-5 EF 2.0 Eutrophication freshwater [g P eq.] per FU – case study #3

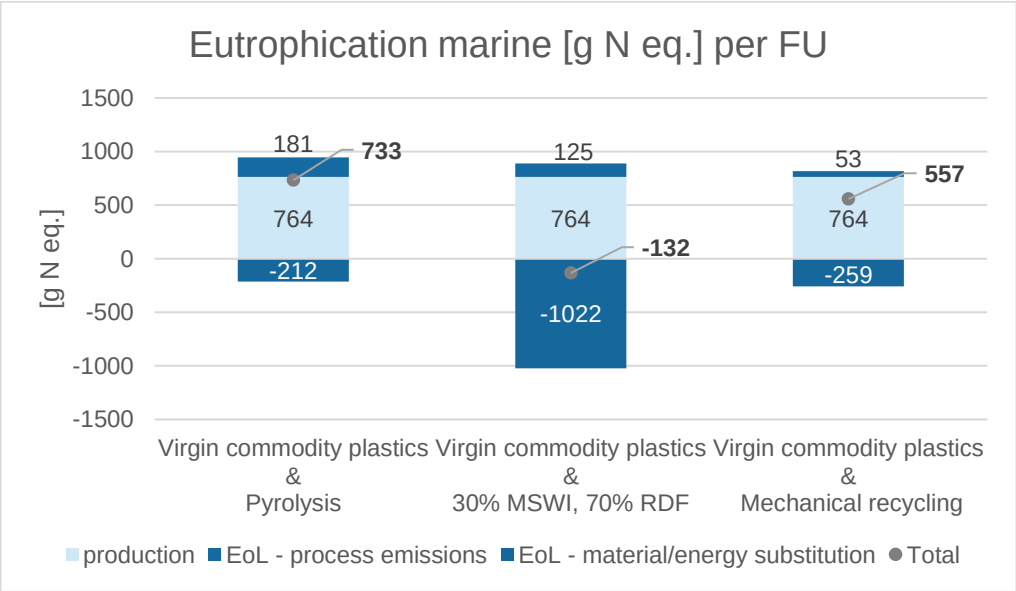


Figure 4-6 EF 2.0 Eutrophication marine [g N eq.] per FU – case study #3

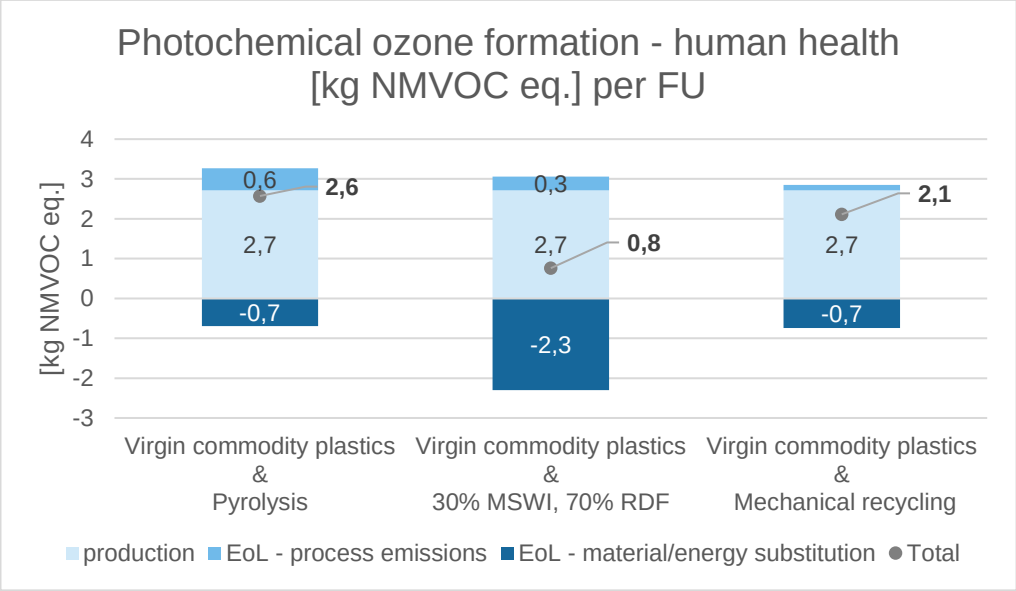


Figure 4-7 EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.] per FU – case study #3

The results for eutrophication freshwater, eutrophication marine and photochemical ozone formation - human health are trend- and content-wise comparable to the results for acidification terrestrial and freshwater, with the exception of eutrophication freshwater. The pyrolysis system has significantly higher results for EP freshwater compared to both comparative systems, incineration and mechanical recycling. That is due to the comparably high energy demand (both electricity and thermal energy) in the pyrolysis and purification step and related to the renewable energy sources within the applied energy mixes.

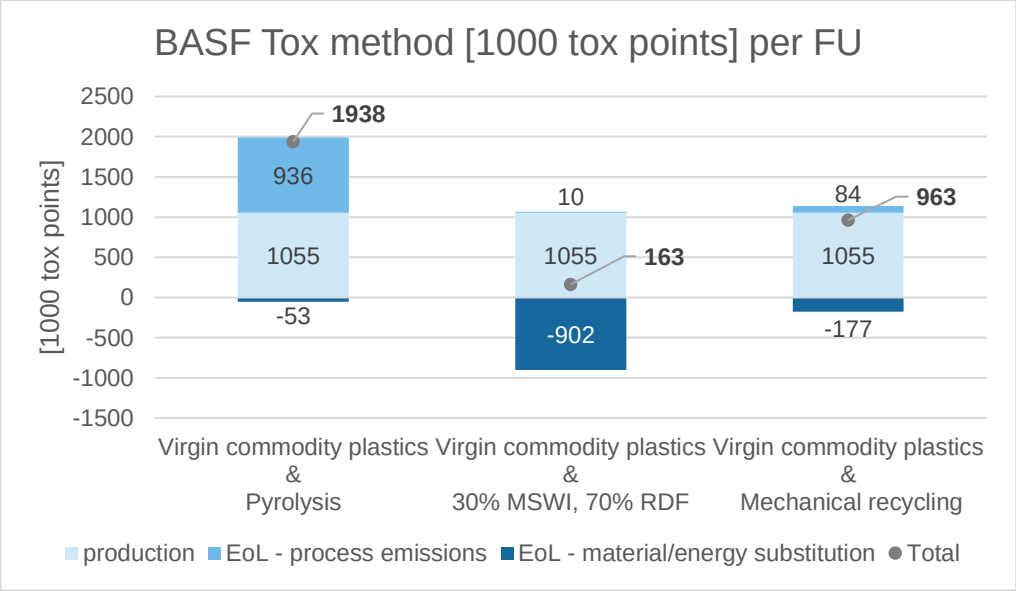


Figure 4-8 BASF Tox method [1000 Tox point] per FU – case study #3

Toxicity results are driven by the process emissions, mainly due to the ethylene production. EoL – credits are mainly driven by substituted energy and electricity. The incineration option shows significantly better results than the recycling options due to its credits.

Analysis of ReCiPe indicators in comparison to assessed impact categories

The ReCiPe indicator results are shown in Annex A. When comparing the assessed categories from Table 2-8 with the ReCiPe indicators, there is no difference in the general trend, with the exception of some toxicity indicators. There is no clear trend for the various human toxicity indicators in EF 2.0, ReCiPe and BASF Tox method. At present, toxicity methods in LCA do not deliver robust results and therefore those results can certainly give additional information for the interpretation of results but should be handled with care in context of drawing conclusions.

Please consider also the effect on the total results of the selected indicators when applying different energy credits as described in the end of section 2.4.1.

4.4.2. Scenario Analysis

Strategies on cutting greenhouse gas emissions which are aiming on short- and long-term targets have been defined by the European Commission (https://ec.europa.eu/clima/policies/strategies_en). Climate Change is therefore a key performance indicator in the waste-to-energy and chemical sectors which is extensively discussed within the group of external and internal stakeholders defined as the intended audience of this study due to the challenges around climate change. As a consequence, the scenarios are analysed for the result indicator climate change based on CO_2-eq only.

Scenario group 1: Technologies considered in the product systems due to system expansion:

For a description of this scenario group, please see section 4.2.4.

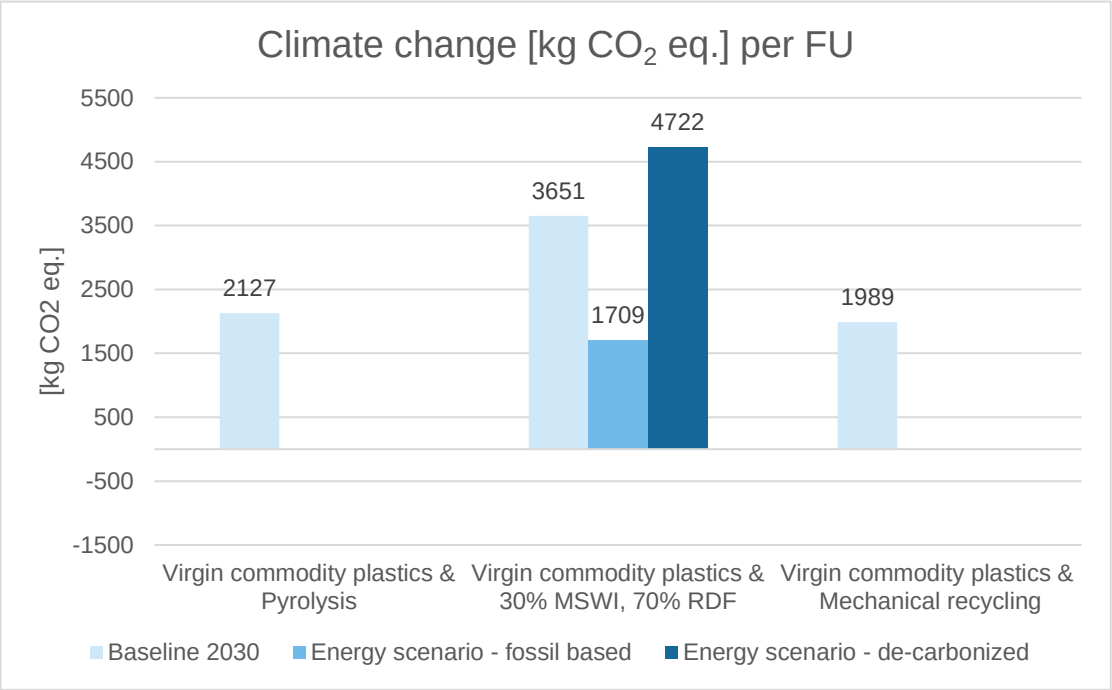


Figure 4-9 Scenario group 1 – case study #3 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

This scenario is used to derive potential LCA results of the assessed systems both in relation to other European countries besides Germany and the future beyond 2040, with >20 years considered as "mid-term" related to sectoral developments.

The range of climate change results for the incineration system is very large considering the extreme cases for the energy credits. The fossil-based scenario has significantly better climate change results than the basic system and has comparable performance to mechanical and pyrolysis. This scenario might be representative for parts of Eastern Europe.

The de-carbonized energy credit scenario could represent the mid-term future for some European countries (e.g. Scandinavian countries), such as in the year 2040 and beyond. The climate change results for the incineration system in 2030 benefits still from partly fossil based energies. In the future as de-carbonization of the industry is the mid-term goal for Germany and other European countries, the incineration system receives much fewer credits from energy recovery.

Thus, the trend in comparison of all systems is significantly affected by the energy recovery burdens due to incineration in the incineration system.

Scenario group 2: Parameter settings for application of CFF - Quality of recyclates

For a description of this scenario group, please see section 4.2.4.

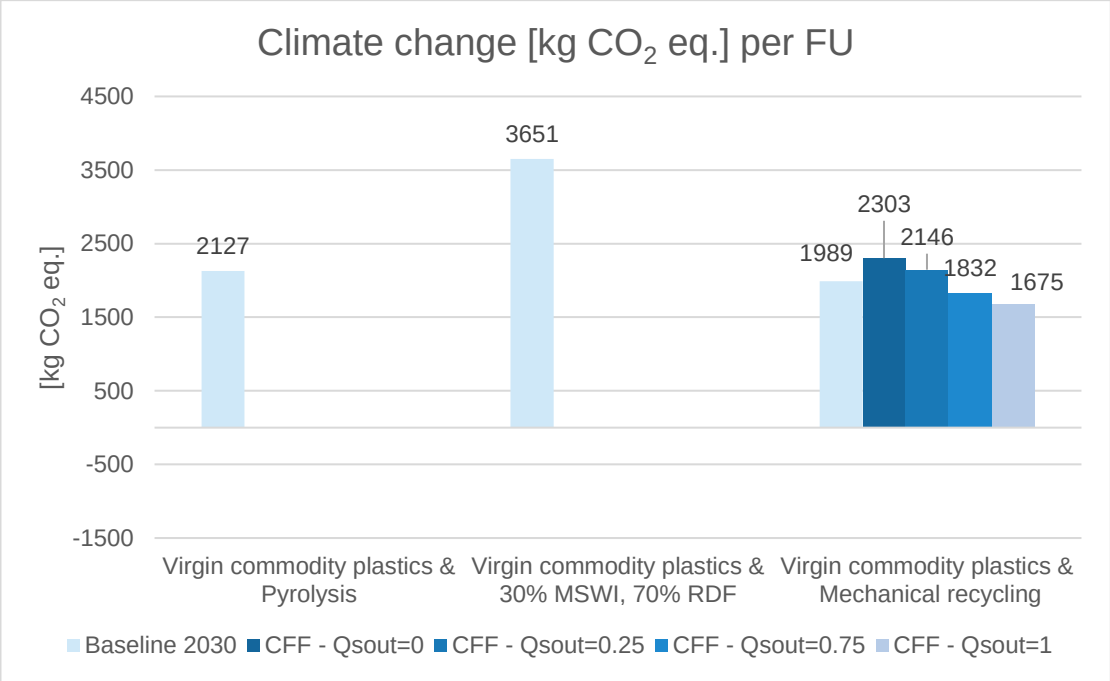


Figure 4-10 Scenario group 2 – case study #3 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

The effect on the total climate change result for the mechanical recycling system is ±16%, so the influence of the product quality is significant. In comparison to the pyrolysis system, the product quality of recyclate determines if mechanical recycling is significantly better or worse regarding the climate change result.

Scenario group 3: Core technologies considered in the product systems: Mechanical recycling – energy efficiency

For a description of this scenario group, please see section 4.2.4.

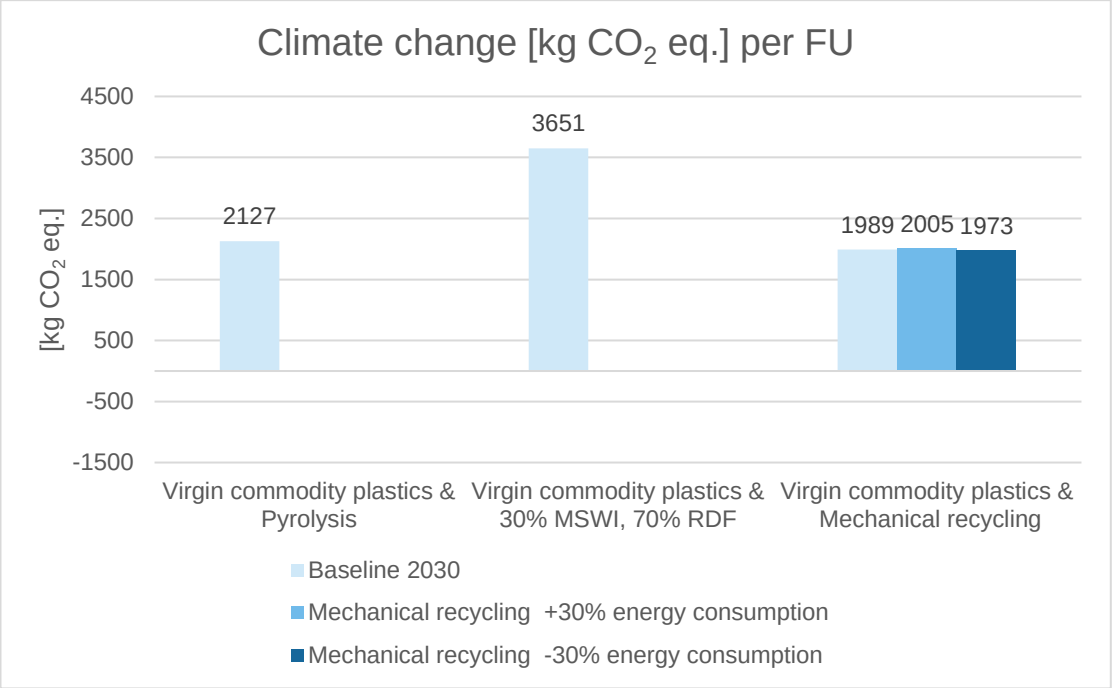


Figure 4-11 Scenario group 3 – case study #3 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

The total climate change results for mechanical recycling changes by ca. ±1%. So, the total results are not sensitive to an altering energy input in mechanical recycling.

The effect is almost linear on the climate change result of the mechanical recycling process only, so ±30% energy input = ±30% climate change result, but this process contributes to only a small fraction of the overall burden over the life cycle.

Scenario group 4: Core technologies considered in the product systems: Mechanical recycling – material efficiency & quality of recyclates

For a description of this scenario group, please see section 4.2.4.

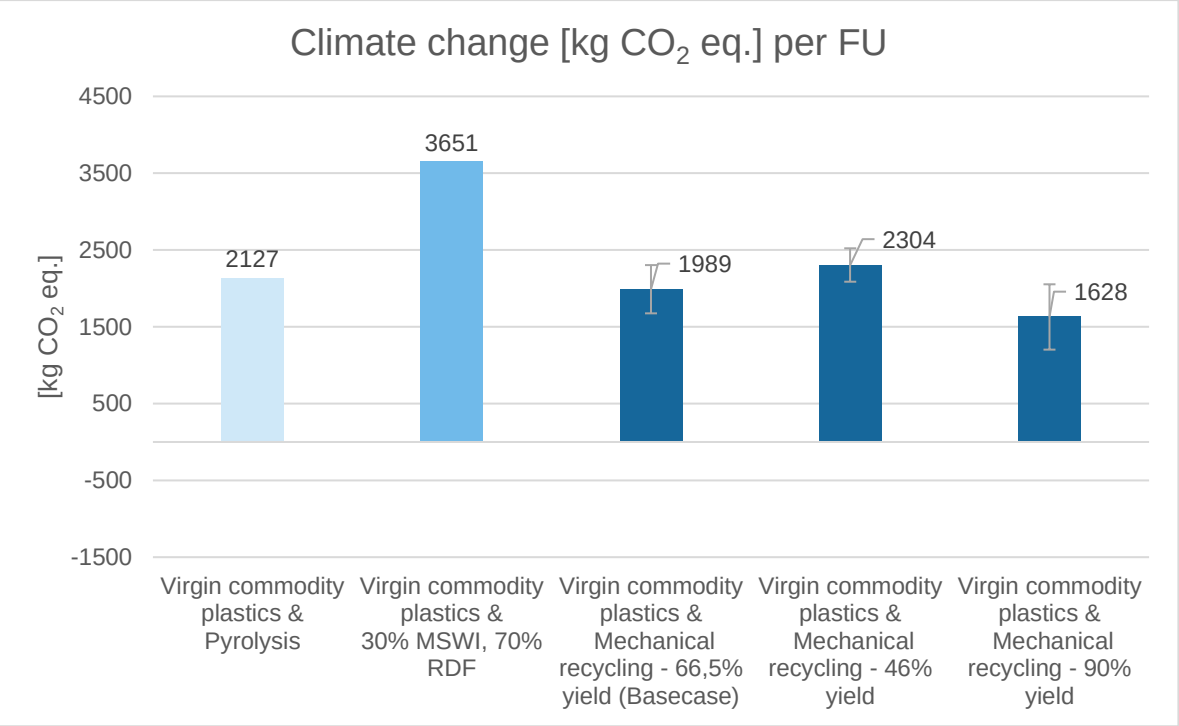


Figure 4-12 Scenario group 4 – case study #3 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

The total climate change results for mechanical recycling changes by +16% for a decreased and -18% for an increased material efficiency, so the influence of material losses is significant. Mechanical recycling in comparison to the pyrolysis system can be significantly better (-23%) regarding the climate change result if the material efficiency increases to 90%.

The effect of the quality of recyclates for the mechanical recycling system on the total climate change result is shown for the base case material efficiency (66,5%) already in Figure 4-10. In Figure 4-12 the variations in climate change results of the quality factors are shown as error bars for specific material efficiencies. A higher material efficiency has got more effect on variation in results. In the base case (66,5% yield) there are ±16%, for a decreased material efficiency (46% yield) there are ±9% and for an increased material efficiency (90% yield) there are about ±26% variations.

The combined effects of material efficiency and recyclate quality results in a variation of +27% (46% yield; Q_{sout} = 0) and -40% (90% yield; Q_{sout} = 1) for mechanical recycling in comparison to the base case results.

In comparison to the pyrolysis system, the combination of the product quality of recyclates with the material efficiency of mechanical recycling determines if mechanical recycling is significantly better or worse regarding the climate change result. The climate change result can be significantly better (-43%) if the material efficiency increases to 90% and the recyclate's quality is virgin-grade (Q_{sout} = 1). However, the result can also be significantly worse (+19%) if the material efficiency decreases to 46% and the recyclate's quality does not allow for further use (Q_{sout} = 0).

Scenario group 5: Parameter settings for application of CFF: A=0 and B=0,5

For a description of this scenario group, please see section 4.2.4.

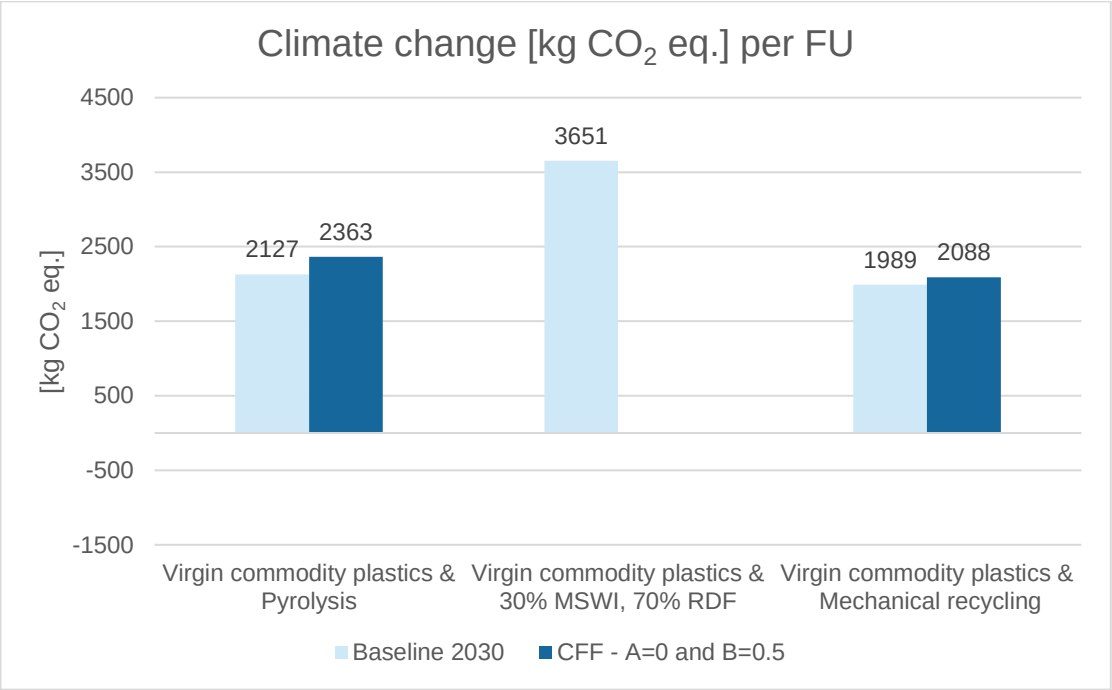


Figure 4-13 Scenario group 5 – case study #3 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

The pyrolysis system has a higher total climate change result with a lower A factor as for climate change the net effect in EoL is negative (net burden in EoL). The MSWI system profits from a higher B factor as the net effect in EoL is negative (net burden in EoL) for climate change as well. For the mechanical system, the dominating positive effect is due to the reduced burden of the incineration of sorted out plastic waste (higher B factor for the energy recovery part of mechanical recycling) as pre-treatment prior to the mechanical recycling process.

Overall, using these parameter settings, mechanical recycling has concerning climate change results a significant advantage compared to pyrolysis and pyrolysis has a significant advantage compared to MSWI.

Scenario group 6: Parameter settings for application of CFF: A=1 and B=0,5

For a description of this scenario group, please see section 4.2.4.

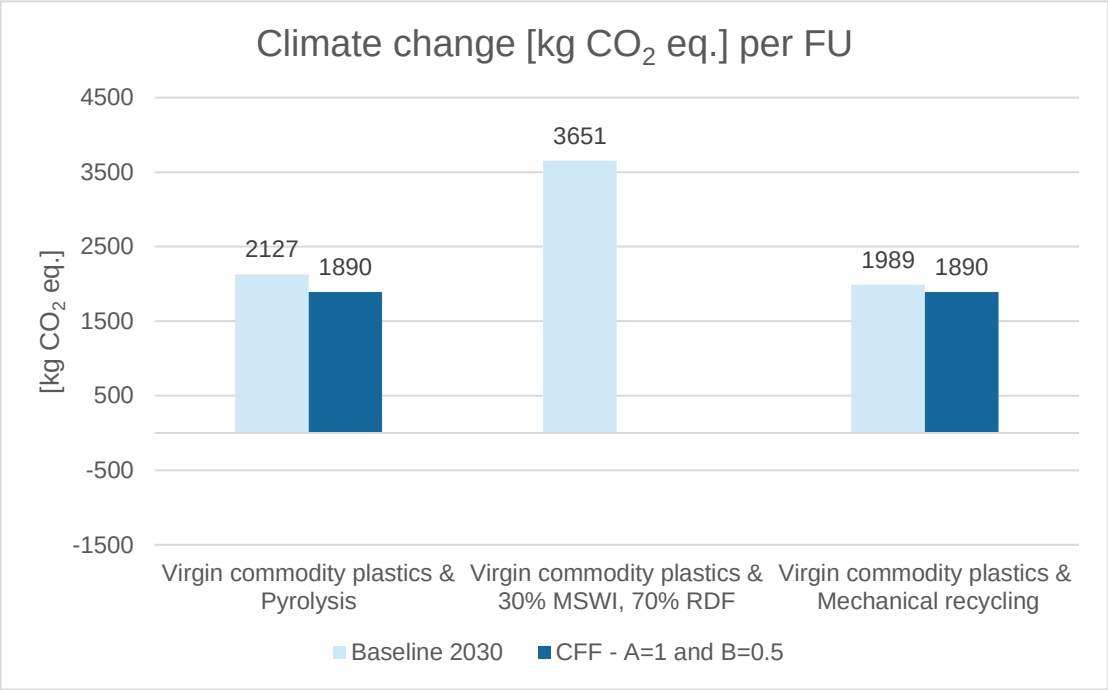


Figure 4-14 Scenario group 6 – case study #3 - EF 2.0 Climate Change [kg CO_2 eq.] per FU

The climate change result for the MSWI system is the same as in scenario 3.1. The cut-off in the EoL phase has a positive effect on the total climate change results for the chemical and mechanical recycling systems, only the burdens of the commodity plastic mix are then considered.

5. Interpretation – all three case studies

5.1. Identification of Relevant Findings

Case study #1 – waste perspective

The goal of this case study was to evaluate the environmental impacts of pyrolysis as end of life option for mixed plastic waste and compare against alternative waste management options including municipal solid waste incineration (MSWI) and refuse derived fuel (RDF). Only the waste processing activities have been assessed with the starting point where waste is collected for treatment (i.e. gate-to-grave scope).

Compared to alternative end of life options comprising 100% MSWI, 100% RDF and a mix of 30% MSWI/70% RDF, pyrolysis has got a clear superior performance for climate change impact.

Although the MSWI and RDF based disposal routes receive significantly greater credits than those for recycling, these are more than outweighed by the much greater emissions from combustion of the plastic waste. The climate change impact is mainly driven by inorganic emissions to air (dominated by CO_2).

A contribution analysis revealed that during pyrolysis, about 66% of the impact is derived from the pyrolysis oil process, while 26% of the impact is caused by waste collection, sorting and transportation. Looking at the incineration processes (MWSI and RDF), the incineration processes clearly dominate the impact generation (~93%), while waste collection, sorting and transportation contribute only to a minor extent (7%) to the results.

Pyrolysis is also the preferred technology for impacts associated with resource use, energy carriers. The energy consumption of the pyrolysis process is significantly greater than that for MSWI or RDF, but this is more than compensated for by the much greater credits obtained from material substitution than from energy substitution in the incineration processes.

However, for other environmental impacts assessed in this study (acidification terrestrial and freshwater, eutrophication freshwater and marine, photochemical ozone formation and human toxicity), the MSWI and RDF technologies outperform pyrolysis as they receive greater credits from energy recovery than are received from the products of pyrolysis.

The ReCiPe indicators show similar trends as the Environmental Footprint 2.0 indicators with some exceptions of certain toxicity indicators. However, since the robustness of toxicity indicators in different LCA methodologies is under discussion, those results should not be overinterpreted. This statement is valid for all three case studies.

A selection of scenario analyses was carried out to test the influence on the climate change results of changing assumptions in the LCA model:

1. Technologies considered in the product systems due to system expansion - influence of different grid mixes for energy credits
2. Target feedstock – economic allocation (increase of MPW prices in sorting plant)
3. Target feedstock – extra effort in the extra sorting step
4. Core technologies considered in the product system – purification efficiency
5. Core technologies considered in the product system – pyrolysis efficiency
6. Further technologies as part of the system – Cement kiln

The key findings of these scenario analyses are the following:

- The level of decarbonisation of the energy mix has a large impact >30% on the credits received by the MSWI and RDF processes. A fully decarbonised energy mix results in much higher impacts for these processes as fewer credits are received from energy recovery. In contrast a fossil-heavy energy mix, boosts these credits to the point where these methods may become preferred over pyrolysis.
- Changing assumptions about the economic value of different waste streams in the sorting plant have a negligible influence on the results of the study.
- Assumed future changes in the composition of MPW and improved sorting technologies would lead to additional effort to produce cleaner waste streams in the sorting plant. However, these assumptions are of minor relevance regarding the climate change result.
- Assumptions relating to the purification efficiency of pyrolysis oil also do not have a very significant impact on the results.
- In contrast, the results are very sensitive to changing assumptions around pyrolysis efficiency. Increasing the carbon conversion efficiency from 71% to 77% and 87% results in reductions in climate change burdens of 27% and 69% respectively.
- A final scenario considered an additional waste treatment route and looked at the use of MPW in cement kilns. If MPW is replaced by a mix of other alternative fuels (such as waste tyres, waste oil, animal fat, mixed fractions of municipal waste, solvents, sewage sludge, oil sludge, organic distillation residues etc.) the burdens from the cement kiln become much higher. This is mainly due to the lower calorific value of some other alternative fuels (e.g. sludge), because higher amounts are needed to compensate MPW. However, if MPW replaces lignite, the results switch, and the cement kiln exhibit much lower carbon footprint. Overall, these results should not be overinterpreted as they are of a very high uncertainty.

Case study #2 - product perspective: virgin-grade quality

The goal of this case study was to evaluate the environmental impacts of pyrolysis as part of the value chain to produce an exemplary chemical product (LDPE) with virgin-grade quality and compare against production of an equivalent product via a conventional virgin polymer route. The scope of the study is up to the point at which the virgin-grade quality product is manufactured. The avoided burdens from not having to dispose of the mixed plastic waste (MPW) by 70% MSWI/30% RDF are considered within the assessment.

In one pathway, a naphtha substitute is produced by pyrolysis of MPW which is fed into a steam cracker and subsequently polymerised (base case) while in the second production technology, virgin LDPE is produced using fossil-based naphtha as feedstock.

Virgin grade LDPE produced from pyrolysis oil from pyrolysis according to the mass balance principle shows significant climate change benefits compared to that produced from fossil-based naphtha. The impacts from the pyrolysis process itself are higher than those for production from naphtha. However, pyrolysis diverts waste from other treatment methods. When the avoided burden from not sending this waste to 70% MSWI/30% RDF are accounted for, significant net credits are received that reduce the climate change impact of the pyrolysis route below that of the fossil-based naphtha route. The indicator climate change is mainly driven by CO_2 emissions to air.

Pyrolysis also outperforms production from naphtha for resource use, energy carriers. In this case the process emissions from the pyrolysis process are ~40% lower than for virgin LDPE production. Natural gas contributes most significantly to the results of the total resource use of energy carriers.

For the other impact categories assessed in this study (acidification terrestrial and freshwater, eutrophication freshwater and marine, photochemical ozone formation), LDPE production from

fossil-based naphtha feedstock is environmentally more favourable than the pyrolysis process. This is mainly due to high emissions in the energy recovery process which are only partly compensated for by prevented emissions due to incineration.

Scenario analyses were carried out to test the influence on the climate change results of changing assumptions in the LCA model.

In case study #2, three scenarios were analysed:

1. Technologies considered in the product systems due to the system expansion - influence of different grid mixes for energy credits
2. Target feedstock – extra effort in the extra sorting step

The key findings of these scenario analyses are the following:

- Assumptions relating to the energy credits received from the avoided MSWI/RDF waste treatment route have a large impact on the results of this case study. The baseline assumption assumed a credit for the predicted 2030 energy mix in Germany. However, if recovered electricity substitutes electricity from a lignite power plant and recovered heat substitutes thermal energy based on heavy fuel oil (HFO), then the climate change of pyrolysis increases greatly. This may be representative of the mid-term future for parts of eastern Europe. However, in the alternative case, where energy mixes are fully decarbonised, the pyrolysis route become much more favourable than the base-case. This may be representative of the mid-term future of countries with more sophisticated industrial and energy processes e.g. Scandinavian countries.
- The second scenario analysis examined the effects on the climate change results from increasing the burdens associated with sorting of the MPW prior to pyrolysis. This had a negligible influence on the results of the study.

A third scenario has not been calculated using a prediction of the future virgin PE production. But it is obvious, that even if the virgin LDPE production improves by 50% - which is highly unlikely - the trend of the total climate change result in comparison of the pyrolysis system including incineration which is prevented is not affected.

Case study #3 – product perspective – various qualities of plastic products

The goal of this case study was to consider the full life cycle of a mix of three commodity plastics (PE, PP, PS) in Germany in the year 2030. The plastics were all produced from fossil-based precursors but sent to three different waste treatment routes at end of life (pyrolysis, mechanical recycling or incineration comprising 70% MSWI, 30% RDF), providing products with different quality levels.

While case study #2 focuses on virgin-grade-quality products, case study #3 covers plastic products with a lower quality level. The Circular Footprint Formula (CFF), developed by the European Commission (2018), was selected as the method for evaluating these differences in quality.

The results of the assessment vary a lot based on the impact category selected.

For climate change impact, there is no significant difference between chemical and mechanical recycling at end of life. In contrast, the incineration treatment option shows much higher burdens for this impact category. The most important factor for the results in the climate change impact category are inorganic emissions to air, particularly CO_2.

Chemical and mechanical recycling also show similar results for acidification and photochemical ozone creation, although incineration is the preferred waste treatment option for these impact categories as it receives very large credits from recovered energy.

For eutrophication, pyrolysis shows higher burdens than mechanical recycling, although, again, incineration is the preferred choice.

For resource use, energy carriers, all three routes have similar impacts.

Scenario analyses were carried out to test the influence on the climate change results of changing assumptions in the LCA model:

1. Technologies considered in the product systems due to system expansion - influence of different grid mixes for energy credits
2. Parameter settings for application of the Circular Footprint Formula: Quality of recyclate (at mechanical recycling)
3. Core technologies considered in the product systems: Mechanical recycling – energy efficiency
4. Core technologies considered in the product systems: Mechanical recycling –material efficiency (in combination with scenario 2 – quality of recyclates)
5. Parameter settings for application of the Circular Footprint Formula:
   A=0; B=0,5 versus A=1; B=0,5

The key findings of these scenario analyses are the following:

- As with case study #1, the level of decarbonisation of the energy mix a large impact on the credits received by the incineration waste management route. A fully decarbonised energy mix results in higher impacts for incineration as fewer credits are received from energy recovery. In contrast a fossil-heavy energy mix boosts these credits to the point where this route become preferred over both chemical and mechanical recycling.
- Variations in recyclate quality obtained from the mechanical recycling route also leads to moderate changes in the results.
- Further scenario analyses examined how changes in energy consumption and material efficiency influence the performance of the mechanical recycling route. Changes in energy consumption of +/-30% were seen to have negligible consequences.
- Changes in material efficiency in a similar range (increased by +37%, decreased by -30%) have a moderate influence.
- The combination of recyclate quality and material efficiency leads to a significant influence on the greenhouse gas emissions for the mechanical recycling system which significantly influences the comparison of these results with those of the pyrolysis technology.
- Variations in the CFF factors A and B result in only modest changes to the results.

5.2. Assumptions and Limitations

A relevant limitation of the LCIA results relative to the defined goal and scope is the assumptions made for setting up all systems to an anticipated situation in 2030 in Germany. However, the validity of the results is supported by various scenario analyses to check potential future developments.

The limitations specifically for the pyrolysis technology are to its disadvantage regarding the LCIA results. So, a conservative approach is followed in context of the main assessed technology. Following aspects highlight this:

A conservative approach has been chosen for the pyrolysis options regarding its yield factor which has been taken from the year 2018 as base case. Potential future developments (e.g. regarding the yield/carbon-conversion efficiency) have been tested in scenarios. A technological advance is expected due to high investments in research and development for pyrolysis.

Nowadays, a relatively pure feedstock (high-calorific MPW) for material recovery is transformed into a relatively pure chemical feedstock, which is currently incinerated in very large quantities in Germany. Due to the estimated shut down of coal-fired power plants in Germany large quantities of high calorific MPW will be available (> 700 kt/a; source: Prof. Meyer, Bergakademie Freiberg). Therefore, a flexibilisation of the feedstock source is not expected for a pyrolysis capacity in Germany of 100-300 kt, if alternative capacities will not be built up. This is currently a matter of discussion between the relevant stakeholders in Germany (politics, industry).

Composition of lightweight packaging waste in the yellow bag might change in the future – that effects on the one hand side the sorting (effect tested in a scenario) and on the other hand side the availability and quality of the target feedstock for pyrolysis. The data for the extra sorting step has been assumed based on available primary data for one sorting plant of mixed waste from yellow bag (source: Meilo, sorting company in Germany). Economic values for the specific waste fractions in sorting plant are estimated by experts and tested in scenarios.

Industry-average data are applied for MSWI, whereas industry-average data will be available for pyrolysis only in 5-10 years. Primary data for the pyrolysis options are based on data of a commercial plant. Its capacities are around 7,5 kt/a pyrolysis oil, whereas large scale data has got around 100-300 kt/a pyrolysis oil produced.

The emission profile of the incineration of high-calorific MPW data is an approximation as it is based on a GaBi dataset with 36 MJ/kg and a defined composition. An adaptation to the target feedstock based on LHV has been performed but not regarding the composition of waste.

The cement kiln scenario settings in case study #1 are based on assumptions and conclusions shall be taken carefully.

The mechanical recycling technology shows relatively high variations in the greenhouse gas emissions depending on certain parameters. Assumptions made for the present study are not suitable for comparing pyrolysis with specific cases of mechanical recycling. As it would go beyond the scope of the present study, specific situations regarding the application case of recyclates, the material efficiency (which depends on the exact fraction / composition of the mixed plastic waste) and the combination of both need to be assessed in a different LCA study.

5.3. Results of Sensitivity and Scenario Analysis

5.3.1. Sensitivity Analysis

Sensitivity analyses were performed to test the sensitivity of the climate change results towards changes in parameter values that are uncertain. Relevant parameters of the mechanical recycling process were checked – the combination of energy input and material loss could be sensitive for the climate change results if both are simultaneously increased or decreased significantly compared to the basic settings.

5.3.2. Scenario Analysis

Scenarios are assessed to check the influence on the overall results of potential divergent developments compared to the baseline situation in the considered technologies. The scenarios are used as well to derive potential LCA results of the assessed systems both in relation to other European countries besides Germany and the future beyond 2040, with >20 years considered as “mid-term” related to sectoral developments.

Scenarios with comparably low relevance are:

- Increased energy efficiency in MSWI
- Increased economic value in sorting plant of MPW fraction
- Increased extra soring effort for MPW to achieve the quality requirements for pyrolysis
- Quality of purified pyrolysis oil
- variations of MPW in cement kiln in comparison to pyrolysis
- energy consumption in mechanical recycling

Scenarios with comparably high relevance are:

- energy credits for recovered energy
- material efficiency of mechanical recycling
- methodological aspects for CFF
    - factor A and B
    - Qsout ratio

The energy credits have a big influence on all result indicators whenever energy is recovered, and energy substitution is applied.

The quality of recyclate as product of mechanical recycling has a significant influence on climate change results. The combination of recyclate quality and material efficiency has an even higher influence. The high variation in GHG results for mechanical recycling shows that specific situations for material losses and product quality in mechanical recycling needs to be assessed in a case-specific context. The product quality depends on the application, the material losses depend on the composition of the mixed plastic waste fraction.

5.4. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, industry data (either primary or secondary data as industry-average) in combination with consistent background LCA information from the GaBi 2019 database were used. The LCI datasets from the GaBi 2019 database are widely distributed and used with the GaBi 9 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.4.1. Precision and Completeness

- **Precision:** As most of the relevant foreground data are either measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be good. Seasonal variations were balanced out by using yearly averages. All background data are sourced from GaBi databases with the documented precision.
- **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is considered to be high. All background data are sourced from GaBi databases with the documented completeness.

5.4.2. Consistency and Reproducibility

- **Consistency:** To ensure data consistency, all data were collected with the same level of detail, while all background data were sourced from the GaBi databases.
- **Reproducibility:** Data on pyrolysis (pyrolysis and purification steps) are confidential, so reproducibility is limited in this regard. Other than that, reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modelling approaches.

5.4.3. Representativeness

- **Temporal:** The relevant data applied in the study were adapted as good as possible to the year 2030. As the study intended to compare the product systems for the reference year 2030, temporal representativeness is considered to be good.
- **Geographical:** All primary and secondary data were collected or adapted specific to the country under study: Germany. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.
- **Technological**: All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be high.

A quantified data quality assessment for the processes of the three case studies is displayed in Annex E.

5.5. Model Completeness and Consistency

5.5.1. Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

5.5.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimised by exclusively using LCI data from the GaBi 2019 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.6. Conclusions

Overall, the results of this study show that pyrolysis can serve as a high value waste management option regarding climate change and material efficiency. As reported above, in two case studies (#1 and #2) assessed in this report, pyrolysis was shown to be the preferred option regarding climate change impact and resource use. For example, pyrolysis is preferred over incineration as an end of

life treatment route and is also preferred over fossil-based naphtha for production of plastic feedstock.

The energy credits given for incineration processes can have a large influence on the climate change results. These credits are sensitive to the composition of the grid mix. It is reasonable to expect that the general trend will be towards grid mixes with an increased share of renewable energy. Scenario analyses showed that higher rates of decarbonisation in grid mixes lead to higher overall climate change values due for incineration routes due to decreased credits at end of life. This means that, over time, the relative benefits of pyrolysis compared to incineration technologies are likely to increase even further.

For other impact categories such as acidification and eutrophication, pyrolysis shows disadvantages as an end of life treatment method compared to incineration, due to the high credits received for recovered energy.

Similarly, when producing plastics using pyrolysis or fossil-based naphtha routes, pyrolysis is preferred for climate change and resources use, but is less favoured for acidification, eutrophication and photochemical ozone formation.

The study gives an overview on environmental impacts linked to different technologies which are applying mixed plastic waste as feedstock. Significant variations in results have been observed for mechanical recycling due to material efficiency and quality of recyclates. Regarding climate change, both pyrolysis and mechanical recycling can have beneficial or adverse effects depending on the application case (quality and composition of waste, application case of products). The respective beneficial application cases (combination of product application and waste fraction) would have to be assessed in specific LCA studies. It has been a decision of the authors to not model these as it would be going beyond the scope of the present study. So, depending on the specific application case, both technologies could be considered as complementary technical solutions for the use of mixed plastic waste rather than competitive in terms of environmental impact.

This means that there is no out-right preferred technology for either treating waste or manufacturing plastics, rather, this will depend upon the impact category that is being assessed. However, looking at current and future global environmental challenges, global warming and the limited availability of non-renewable resources are, and will be, crucial for sustainable business and production practices. On these key measures, pyrolysis is shown to deliver significant potential benefits.

The quality of the results is strongly correlated to the quality of data used for calculation of the results. In this study, assumptions and approximations had to be made for certain important parameters (e.g. the purification and pyrolysis steps in the pyrolysis process). Collecting more precise data on these processes would lead to more robust and transparent results.

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Annex A: LCIA Results – all indicators

Case study #1

Table A-0-1 LCIA for case study #1 – EF 2.0 and BASF

	Pyrolysis	100% MSWI	100% RDF	30% MSWI, 70% RDF
EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	-0,6	-2,0	-2,5	-2,3
EF 2.0 Cancer human health effects [1.000.000 CTUh]	-14,2	-1,6	-1,9	-1,8
EF 2.0 Climate Change [kg CO2 eq.]	739,1	1919,1	1716,2	1777,1
EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	-0,1	-30,6	-34,7	-33,5
EF 2.0 Climate Change (fossil) [kg CO2 eq.]	739,3	1959,5	1762,1	1821,3
EF 2.0 Climate Change (land use change) [kg CO2 eq.]	-0,1	-9,8	-11,2	-10,8
EF 2.0 Ecotoxicity freshwater [CTUe]	-243,8	456,0	441,9	446,1
EF 2.0 Eutrophication freshwater [g P eq.]	0,1	-18,7	-21,2	-20,5
EF 2.0 Eutrophication marine [g N eq.]	-44,1	-756,5	-896,3	-854,3
EF 2.0 Eutrophication terrestrial [Mole of N eq.]	-0,4	-6,2	-7,6	-7,2
EF 2.0 Ionising radiation - human health [kBq U235 eq.]	-0,8	1,5	0,3	0,7
EF 2.0 Land Use [1000 Pt]	-0,9	-69,4	-78,6	-75,9
EF 2.0 Non-cancer human health effects [100.000 CTUh]	2,1	-1,2	-1,8	-1,6
EF 2.0 Ozone depletion [pg CFC-11 eq.]	4,2	-0,08	-1,0	-0,09
EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	-0,4	-1,6	-2,0	-1,9
EF 2.0 Resource use, energy carriers [GJ]	-26,6	-13,1	-15,5	-14,8
EF 2.0 Resource use, mineral and metals [mg Sb eq.]	0,3	-1,0	-1,3	-1,2
EF 2.0 Respiratory inorganics [100.000 Deaths]	-0,3	-1,2	-1,5	-1,4
EF 2.0 Water scarcity [m³ world equiv.]	106,0	271,1	263,1	265,5
BASF Tox method [1000 Tox point]	-579,9	-690,3	-894,3	-833,1

Table A-0-2 LCIA for case study #1 – ReCiPe 2016 v1.1 Midpoint (H)

	Pyrolysis	100% MSWI	100% RDF	30% MSWI, 70% RDF
Climate change, default, excl biogenic carbon [kg CO2 eq.]	740,8	1930,7	1729,7	1790,0
Fine Particulate Matter Formation [g PM2.5 eq.]	-129,9	-382,9	-463,7	-439,5
Fossil depletion [kg oil eq.]	-621,6	-315,2	-373,4	-355,9
Freshwater Consumption [m3]	55,0	5,0	4,4	4,6
Freshwater ecotoxicity [g 1,4 DB eq.]	-351,8	93,6	70,5	77,4
Freshwater Eutrophication [g P eq.]	0,1	-18,7	-21,2	-20,5
Human toxicity, cancer [kg 1,4-DB eq.]	-0,4	-0,7	-0,9	-0,8
Human toxicity, non-cancer [kg 1,4-DB eq.]	-141,8	20,4	13,5	15,6
Ionizing Radiation [Bq C-60 eq. to air]	-0,2	0,3	0,1	0,2
Land use [Annual crop eq.·y]	-4,3	-368,1	-417,3	-402,5
Marine ecotoxicity [kg 1,4-DB eq.]	-0,8	2,5	2,4	2,5
Marine Eutrophication [g N eq.]	-0,6	-122,9	-139,6	-134,6
Metal depletion [kg Cu eq.]	2,2	5,5	4,6	4,9
Photochemical Ozone Formation, Ecosystems [g NOx eq.]	-194,1	-1443,2	-1732,3	-1645,6
Photochemical Ozone Formation, Human Health [g NOx eq.]	-168,1	-1429,5	-1715,9	-1630,0
Stratospheric Ozone Depletion [g CFC-11 eq.]	0,0	-1,1	-1,2	-1,2
Terrestrial Acidification [kg SO2 eq.]	-0,4	-1,3	-1,5	-1,4
Terrestrial ecotoxicity [kg 1,4-DB eq.]	388,4	1366,5	1170,4	1229,3

Case study #2

Table A-0-3 LCIA for case study #2 – EF 2.0 and BASF

	Pyrolysis - avoided emissions (30% MSWI, 70% RDF)	Virgin PE
EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	6,7	3,0
EF 2.0 Cancer human health effects [0.000001 CTUh]	4,7	18,7
EF 2.0 Climate Change [kg CO2 eq.]	-446,8	1894,3
EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	71,3	4,4
EF 2.0 Climate Change (fossil) [kg CO2 eq.]	-541,1	1888,3
EF 2.0 Climate Change (land use change) [kg CO2 eq.]	23,0	1,5
EF 2.0 Ecotoxicity freshwater [CTUe]	-769,2	428,4
EF 2.0 Eutrophication freshwater [g P eq.]	45,1	3,4
EF 2.0 Eutrophication marine [g N eq.]	2,3	0,8
EF 2.0 Eutrophication terrestrial [Mole of N eq.]	20,8	8,1
EF 2.0 Ionising radiation - human health [kBq U235 eq.]	6,6	67,5
EF 2.0 Land Use [1000 Pt]	159,1	7,5
EF 2.0 Non-cancer human health effects [0.00001 CTUh]	9,6	2,2
EF 2.0 Ozone depletion [ng CFC-11 eq.]	8,8	0,02
EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	5,6	2,5
EF 2.0 Resource use, energy carriers [GJ]	42,9	69,4
EF 2.0 Resource use, mineral and metals [mg Sb eq.]	3,7	0,4
EF 2.0 Respiratory inorganics [0.00001 Deaths]	4,7	2,2
EF 2.0 Water scarcity [m³ world equiv.]	-326,2	-27,2
BASF Tox method [1000 Tox point]	5052,9	192,0

Table A-0-4 LCIA for case study #2 – ReCiPe 2016 v1.1 Midpoint (H)

	Pyrolysis - avoided emissions (30% MSWI, 70% RDF)	Virgin PE
Climate change, default, excl biogenic carbon [kg CO2 eq.]	-481,3	1885,5
Fine Particulate Matter Formation [kg PM2.5 eq.]	1,3	0,6
Fossil depletion [kg oil eq.]	1028,6	1645,3
Freshwater Consumption [m3]	107,1	8,1
Freshwater ecotoxicity [g 1,4 DB eq.]	-51,3	573,8
Freshwater Eutrophication [g P eq.]	45,1	3,4
Human toxicity, cancer [kg 1,4-DB eq.]	2,3	1,1
Human toxicity, non-cancer [kg 1,4-DB eq.]	4,7	204,1
Ionizing Radiation [Bq C-60 eq. to air]	0,9	11,3
Land use [Annual crop eq.·y]	847,1	43,9
Marine ecotoxicity [kg 1,4-DB eq.]	-4,0	1,7
Marine Eutrophication [g N eq.]	291,0	29,5
Metal depletion [kg Cu eq.]	-4,2	1,6
Photochemical Ozone Formation, Ecosystems [kg NOx eq.]	4,7	2,0
Photochemical Ozone Formation, Human Health [kg NOx eq.]	4,7	1,9
Stratospheric Ozone Depletion [g CFC-11 eq.]	2,7	0,5
Terrestrial Acidification [kg SO2 eq.]	4,1	1,9
Terrestrial ecotoxicity [kg 1,4-DB eq.]	-1103,0	294,6

Case study #3

Table A-0-5 LCIA for case study #3 – EF 2.0 and BASF

	Virgin-grade commodity plastics & Pyrolysis	High quality commodity plastics & (30% MSWI, 70% RDF)	Virgin-grade commodity plastics & Mechanical recycling
EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	2,8	0,5	3
EF 2.0 Cancer human health effects [0.000001 CTUh]	14,2	17,1	15,7
EF 2.0 Climate Change [kg CO2 eq.]	2126,7	3651,3	1989,0
EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	4,3	-31,3	-1,4
EF 2.0 Climate Change (fossil) [kg CO2 eq.]	2120,9	3692,7	1990,8
EF 2.0 Climate Change (land use change) [kg CO2 eq.]	1,5	-10,0	-0,4
EF 2.0 Ecotoxicity freshwater [CTUe]	326,1	879,6	441,2
EF 2.0 Eutrophication freshwater [g P eq.]	3,7	-18,3	-0,2
EF 2.0 Eutrophication marine [g N eq.]	732,9	-132,5	557,5
EF 2.0 Eutrophication terrestrial [Mole of N eq.]	7,7	0,4	6,2
EF 2.0 Ionising radiation - human health [kBq U235 eq.]	36,0	53,0	44,7
EF 2.0 Land Use [1000 Pt]	7,9	-72,9	-5,1
EF 2.0 Non-cancer human health effects [0.00001 CTUh]	2,9	0,0	1,6
EF 2.0 Ozone depletion [ng CFC-11 eq.]	23,8	-0,9	0,1
EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	2,6	0,8	2,1
EF 2.0 Resource use, energy carriers [GJ]	53,7	53,2	56,1
EF 2.0 Resource use, mineral and metals [g Sb eq.]	0,6	-1,0	0,3
EF 2.0 Respiratory inorganics [0.00001 Deaths]	2,0	0,6	1,7
EF 2.0 Water scarcity [m^3 world equiv.]	60,4	277,0	56,9
BASF Tox method (2018) [1000 Tox point]	1938,5	163,4	962,9

Table A-0-6 LCIA for case study #3 – ReCiPe 2016 v1.1 Midpoint (H)

	Virgin-grade commodity plastics & Pyrolysis	High quality commodity plastics & (30% MSWI, 70% RDF)	Virgin-grade commodity plastics & Mechanical recycling
Climate change, default, excl biogenic carbon [kg CO2 eq.]	2118,0	3656,4	1983,5
Climate change, incl biogenic carbon [kg CO2 eq.]	2125,8	3661,3	1986,0
Fine Particulate Matter Formation [kg PM2.5 eq.]	0,5	0,1	0,5
Fossil depletion [kg oil eq.]	1273,8	1255,3	1328,3
Freshwater Consumption [m3]	37,7	12,8	8,0
Freshwater ecotoxicity [kg 1,4 DB eq.]	0,4	0,6	0,5
Freshwater Eutrophication [g P eq.]	3,7	-18,3	-0,2
Human toxicity, cancer [kg 1,4-DB eq.]	1,0	0,2	0,8
Human toxicity, non-cancer [kg 1,4-DB eq.]	157,1	218,3	177,6
Ionizing Radiation [Bq C-60 eq. to air]	6,0	8,9	7,5
Land use [Annual crop eq.·y]	44,8	-383,5	-23,9
Marine ecotoxicity [kg 1,4-DB eq.]	1,4	4,2	1,9
Marine Eutrophication [g N eq.]	27,0	-114,3	3,9
Metal depletion [kg Cu eq.]	2,1	6,1	2,3
Photochemical Ozone Formation, Ecosystems [kg NOx eq.]	1,9	0,3	1,5
Photochemical Ozone Formation, Human Health [kg NOx eq.]	1,8	0,2	1,5
Stratospheric Ozone Depletion [g CFC-11 eq.]	0,4	-0,8	0,2
Terrestrial Acidification [kg SO2 eq.]	1,8	0,4	1,5
Terrestrial ecotoxicity [kg 1,4-DB eq.]	469,9	1462,4	575,6

Annex B: Critical Review Statement

Background

The life cycle assessment (LCA) study "Evaluation of pyrolysis with LCA" was commissioned by BASF and carried out by Sphera. The study was critically reviewed by an international panel of experts comprising:

- Professor Adisa Azapagic (Panel Chair), Ethos Research, UK;
- Dr Florian Antony, Institute for Applied Ecology, Germany; and
- Simon Hann, Eunomia Research & Consulting Ltd., UK.

All members of the review panel were independent of any party with a commercial interest in the study.

The aim of the review was to ensure that:

- the methods used to carry out the LCA study are consistent with the ISO 14040:2006 and 14044:2006 standards;
- the methods used are scientifically and technically valid given the goal of the study;
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretation of the results and the conclusions of the study reflect the goal and the findings of the study; and
- the study report is transparent and consistent.

The critical-review process involved the following:

- a review of the goal and scope definition at the outset of the project;
- a review of three versions of draft reports according to the above criteria and recommendations for improvements to the study and the report; and
- a review of the fourth and final version of the report, in which the authors of the study fully addressed the points as suggested in the draft critical review.

The critical review panel did not review the LCA models developed by Sphera for the purposes of this project and hence all the findings of the critical review are based solely on the LCA report that was made available to the panel during the course of the critical review.

Conclusion of the critical review

The panel confirms that this LCA study followed the guidance of and is consistent with the international standards for Life Cycle Assessment (ISO 14040:2006 and 14044:2006).

Communication of the study results

The following aspects should be mentioned when communicating the results of the study to external stakeholders:

- Some of the assumptions affect the results, interpretation and conclusions of the study. Therefore, it is of utmost importance that these and their influence on the results and conclusions are described transparently, whenever the study or its parts are disclosed to any stakeholders to avoid any potential misinterpretation of the study.
- The study is based on an assumed future development of pyrolysis and the waste sector in Germany in 2030 and thus the results should be interpreted with this in mind. To reduce the uncertainty and increase the robustness of the study, the assumptions and the results should be reviewed again as soon as more detailed information becomes available.
- It should always be mentioned that Cases #2 and #3 are based on the mass balance approach. Although this has been applied rigorously, it is important to state this clearly in any future communication to maintain the transparency of the study.
- The comparison of pyrolysis with the alternative methods is based on the assumption that a difference of 10% is considered 'significant' when comparing the results of the life cycle impact assessment. This is a subjective assumption and should be interpreted accordingly. This is particularly important for impact categories with higher uncertainty, such as toxicity-related impacts where the margin for error is likely to be greater than 10%.
- Whenever a reference is made to the review of the study and its outcome, it should also be mentioned that the critical review statement is available upon request.

Professor Adisa Azapagic	Dr Florian Antony	Simon Hann
Panel Chair	Panel Member	Panel Member

April 2020

Annex C: Confidential Data

Table C-0-7 Commodity plastics composition

Flow	Value	Unit	DQI*
Polypropylene	33	%	Estimated by expert
Polyethylene	51	%	Estimated by expert
Polystyrene	16	%	Estimated by expert

Source; (BASF, Technical information from BASF experts, 2019)

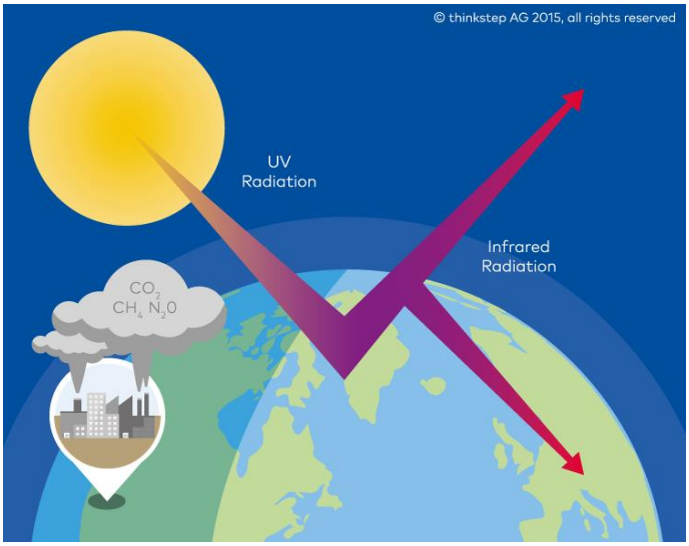
Annex D: Impact category description

Climate Change - Global Warming Potential (GWP100)

The mechanism of the greenhouse effect can be observed on a small scale, as the name suggests, in a greenhouse. These effects also occur on a global scale. The occurring short-wave radiation from the sun comes into contact with the earth's surface and is partially absorbed (leading to direct warming) and partially reflected as infrared radiation. The reflected part is absorbed by greenhouse gases in the troposphere and is re-radiated in all directions, including back to earth. This results in a warming effect at the earth's surface.

In addition to the natural mechanism, the greenhouse effect is enhanced by human activities. Greenhouse gases, believed to be anthropogenically caused or increased, include carbon dioxide, methane and CFCs. Figure below shows the main processes of the anthropogenic greenhouse effect. An analysis of the greenhouse effect should consider the possible long-term global effects.

The global warming potential is calculated in carbon dioxide equivalents (CO_2-Eq.), meaning that the greenhouse potential of an emission is given in relation to CO_2. Since the residence time of gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified. A usual period is 100 years.



Unit: kg CO_2 equivalent

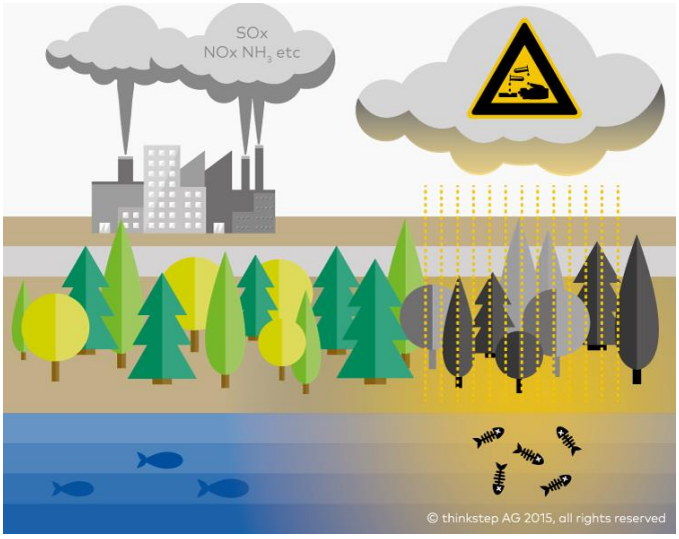
Reference: **(IPCC, 2013)**

EF 2.0: The PEF climate change operates with characterisation factors described in the Assessment Report (AR) 5 with additional inclusion of climate carbon feedback. VOC (unspecified) has a characterization factor of 4,23 in EF 2.0. The BASF climate change method has a factor of 0.

__ReCiPe 2016:__ Hierarchical (H) covers what is considered the default timeframe of 100 years (GWP100) supplemented with Climate-carbon feedbacks from the supplementary material of AR5. As default, ReCiPe operates excl. biogenic carbon and hence the biogenic methane has a slightly reduced climate change factor, like the calculation above. A secondary climate change impact including biogenic carbon is added for each cultural perspective. This means including CO_2 uptake and biogenic CO_2 emission, plus giving biogenic methane emission a characterisation factors identical to the fossil versions. The CO2 factor for land use change (LUC) is 1 in the BASF specific method and EF 2.0 and 0 as default for ReCiPe. There is a separate climate change indicator including LUC in ReCiPe.

Acidification Potential (AP)

The acidification of soils and waters occurs predominantly through the transformation of air pollutants into acids. This leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and below. Sulphur dioxide and nitrogen oxide and their respective acids (H_2SO_4 und HNO_3) produce relevant contributions. Ecosystems are damaged, so forest dieback is the most well-known impact as indicated in Figure below.
Acidification has direct and indirect damaging effects (such as nutrients being washed out of soils or an increased solubility of metals into soils). But even buildings and building materials can be damaged. Examples include metals and natural stones, which are corroded or disintegrated at an increased rate.
When analysing acidification, it should be considered that although it is a global problem, the regional effects of acidification can vary.



Unit: Mole of H+ equivalent

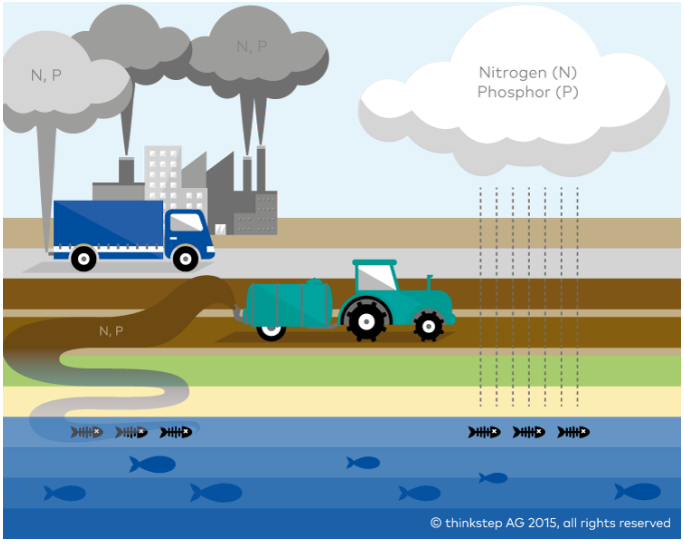
Reference: (Seppälä et al, 2006) (Posch et al, 2008)

EF 2.0: The EF setup uses Accumulated Exceedance (AE). AE uses atmospheric models to calculate the deposition of released acidifying and eutrophying substance per release country and relates this value to the capacity of the receiving soil to neutralize the effects. The method integrates both the exceeded area and amount of exceedance per kg of released substance. In GaBi, only a global value for the acidification is implemented.

ReCiPe 2016: *The acidification potential is given in sulphur dioxide equivalents (SO_2-Eq.). The acidification potential is described as the ability of certain substances to build and release H^+ ions. Certain emissions can also have an acidification potential, if the given S-, N- and halogen atoms are set in proportion to the molecular mass of the emission. The reference substance is sulphur dioxide. Regional factors have not been adopted as the baseline, because it is not always possible, nor desirable, to consider differences between emission sites in LCA.*

Eutrophication Potential (EP)

Eutrophication is the enrichment of nutrients in a certain place. Eutrophication can be aquatic or terrestrial. Air pollutants, wastewater and fertilisation in agriculture all contribute to eutrophication as indicated in Figure below.
The result in water is an accelerated algae growth, which in turn, prevents sunlight from reaching the lower depths. This leads to a decrease in photosynthesis and less oxygen production. Oxygen is also needed for the decomposition of dead algae. Both effects cause a decreased oxygen concentration in the water, which can eventually lead to fish dying and to anaerobic decomposition (decomposition without the presence of oxygen). Hydrogen sulphide and methane are produced. This can lead to the destruction of the eco-system, among other consequences.
On eutrophicated soils, an increased susceptibility of plants to diseases and pests is often observed, as is degradation of plant stability. If the nutrification level exceeds the amounts of nitrogen necessary for a maximum harvest, it can lead to an enrichment of nitrate. This can cause, by means of leaching, increased nitrate content in groundwater. Nitrate also ends up in drinking water.



Unit: EP freshwater: kg P equivalent. EP marine: kg N equivalent
Reference: (Struijs et al., 2009)
EF 2.0: The EF setup uses EUTREND model as implemented in ReCiPe – with the fraction of nutrients reaching freshwater end compartment (P) and the fraction of nutrients reaching marine end compartment (N)
ReCiPe 2016: *same as EF 2.0*

Photochemical ozone formation, human health

Despite playing a protective role in the stratosphere, ozone at ground level is classified as a damaging trace gas. Photochemical ozone production in the troposphere, also known as summer smog, is suspected to damage vegetation and material. High concentrations of ozone are toxic to humans.

Radiation from the sun and the presence of nitrogen oxides and hydrocarbons incur complex chemical reactions, producing aggressive reaction products, one of which is ozone. Nitrogen oxides alone do not cause high ozone concentration levels. Hydrocarbon emissions occur from incomplete combustion, in conjunction with petrol (storage, turnover, refuelling) or from solvents. High concentrations of ozone arise when temperature is high, humidity is low, air is relatively static and there are high concentrations of hydrocarbons. Today it is assumed that the existence of NO and CO reduces the accumulated ozone to NO_2, CO_2 and O_2. This means that high concentrations of ozone do not often occur near hydrocarbon emission sources. Higher ozone concentrations more commonly arise in areas of clean air, such as forests, where there is less NO and CO.

Unit: kg NOx equivalent
Reference: (van Zelm et al.:, 2008)
EF 2.0: The dynamic model LOTOS-EUROS was applied to calculate intake fractions for ozone due to emissions of NO_x. The mid-point characterisation factor for ozone formation of a substance is defined as the marginal change in the 24h-average European concentration of ozone (in kg/m^3) due to a marginal change in emission (in kg/year). It is expressed as NOx equivalents.
ReCiPe 2016: *same as EF 2.0*

Resource use, fossils

The abiotic depletion potential (ADP) covers some selected natural resources as metal-containing ores, crude oil and mineral raw materials. Abiotic resources include raw materials from non-living resources that are non-renewable. This impact category describes the reduction of the global amount of non-renewable raw materials. Non-renewable means a time frame of at least 500 years. The abiotic depletion potential is split into two sub-categories, elements and fossil.

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Unit: kg oil equivalents
Reference: (Guinée, et al., 2002)
EF 2.0: The sub-category abiotic depletion potential (fossil) includes the fossil energy carriers (crude oil, natural gas, coal resources). The actual list of characterization factors from CML contains only one example of each energy carrier with a specific calorific value but with a characterization factor equal to the lower calorific value. Uranium is accounted for in ADP (elements) and is not listed as a fossil fuel.
ReCiPe 2016: *applies the unit kg oil equivalents*

Human Toxicity (BASF method)

The human toxicity potential takes into consideration all substances handled at any time during the life cycle of a product. Only toxicity potentials are assessed, not actual risks. Substances are assigned toxicity points based on their hazard phrases (H-phrases) of the Globally Harmonized System (GHS). The H-phrases indicate human health hazards associated with exposure to specific substances. These toxicity points are multiplied with the amounts of substances used to report life cycle human toxicity potentials expressed in terms of dimensionless toxicity points. Toxicity points were assigned by toxicologists to each H-phrase. For example, the classification H330 (fatal if inhaled) was assigned 750 toxicity points and the considerably less critical category H312 (harmful in contact with skin) 300 points.

Unit: Tox points
Reference: (Landsiedel & Saling, 2002)
EF 2.0 and ReCiPe: different toxicity methods applied

Annex E: Data quality assessment

Process name	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Mixed waste collection and sorting	2	3	3	2	2
Mixed plastic waste – extra sorting	2	3	3	2	2
Pyrolysis and purification step	2	2	3	3	2
Municipal Solid Waste Incineration	2	1	3	2	1
Refuse Derived Fuel	2	1	3	2	1
Cement clinker production	2	1	3	2	1
Cracking	2	1	3	2	1
Polymerization	2	1	3	2	1
Mechanical recycling	2	2	3	2	2
German electricity mix 2030	2	1	2	1	2
German thermal energy mix 2030	2	1	2	1	2
Nitrogen allocated by volume	2	1	4	2	2
Compressed air	2	1	4	2	2
Hydrogen 25 bar	2	1	4	2	2
Sodium methylate, 30% solution in Methanol	2	1	4	2	2
Tap water from groundwater	2	1	4	2	2
Demineralized Water LU (Water 0% consumptive)	2	1	4	2	2

Process name	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Municipal wastewater treatment (mix)	2	1	4	2	2
Lignite mix	2	1	4	2	2
Naphtha at refinery	2	1	4	2	1
Heavy Vacuum Residue	2	2	4	3	2
Cooling water from river	2	2	4	3	2
Natural gas mix	2	2	4	2	2
Sodium hydroxide	2	2	4	2	2
Polyethylene Low Density Granulate (LDPE/PE-LD)	2	2	4	2	1
Polyethylene Low Density Granulate – polymerization process	2	2	4	2	1
Polystyrene granulate (PS)	2	2	4	2	1
Polypropylene granulate (PP)	2	2	4	2	1
Nitrogen via cryogenic air separation production mix, at plant liquid	2	2	4	2	2
Rail transport cargo - Electric, average train, gross tonne weight 1,000t / 726t payload capacity	2	2	4	3	2
Truck-trailer, Euro 6, up to 28t gross weight / 12.4t payload capacity	2	2	4	3	2
Diesel mix at filling station	2	2	4	2	2