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# Greenhouse gas emissions and natural capital implications of plastics (including biobased plastics)

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# Acronyms

| | |
|---|---|
| ABS | Acrylonitril-butadiene-styrene |
| APC | Aliphatic polycarbonate |
| BBP | Benzylbutylphtalate |
| BPA | Bisphenol A |
| BTX | Benzene-toluene-xylene |
| C | Carbon |
| CA | Cellulose acetate |
| CEPI | Confederation of European Paper Industries |
| CI | Carbon intensity |
| CIS | Commonwealth of Independent States: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine and Uzbekistan |
| $CO_2$ | Carbon dioxide |
| $CO_2$ eq | Carbon dioxide equivalent |
| DBDPE | Decabromodiphenylethane |
| DBP | Dibutyl phosphate |
| DEHP | Di(2-ethylhexyl) phthalate |
| DMT | Dimethyl terephthalate |
| DIDP | Diisodecyl phthalate |
| DINP | Diisononyl phthalate |
| DNOP | Di-n-octylphthalate |
| DMT | Dimethyl terephthalate |
| DPET | Direct polyethylene terephthalate |
| EEA | European Environment Agency |
| EMF | Ellen McArthur Foundation |
| EoL | End of life |
| EPDM | Ethylene propylene diene monomer rubber |
| EPRTR | European Pollutant Release and Transfer Register |
| EPS | Expanded polystyrene |
| EU | European Union |
| g | gram |
| GHG | Greenhouse gas |
| Gt | Gigatonne ($10^9$ tonnes) |
| GWP | Global warming potential |

| | |
|---|---|
| HD PE | High-density polyethylene |
| HWP | Harvested wood products |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| IPPC | Integrated Pollution Prevention and Control |
| JRC | Joint Research Centre |
| Kg | Kilogramme |
| kt | Kilotonne (1,000 tonnes) |
| LCA | Lifecycle assessment |
| LCT | Lifecycle thinking |
| LD PE | Low-density polyethylene |
| LLD PE | Linear low-density polyethylene |
| LPG | Liquefied petroleum gas |
| MD PE | Medium-density polyethylene |
| MEK | Methyl ethyl ketone |
| MJ | Megajoule ($10^6$ joules) |
| MTA | Methanol to aromatics |
| MTBE | Methyl tert-butyl ether |
| MTO | Methanol to olefins |
| Mt | Million tonnes |
| MTP | Methanol to propylene |
| NGL | Natural gas liquids |
| NOx | Nitrogen oxides |
| OBDE | Octabromodiphenyl ether |
| OECD | Organisation for Economic Co-operation and Development |
| PA | Polyamide |
| PBAT | Polybutyrate adipate terephthalate |
| PBS | Polybutylene succinate |
| PBT | Polybutylene terephthalate |
| PBAT | Polybutylene adipate-co- terephthalate |
| PC | Polycarbonate |
| PCL | Polycaprolactone |
| PE | Polyethylene |
| PEBDE | Pentabromodiphenyl ether |
| PEF | Polyethylene furanoate |
| PET | Polyethylene terephthalate |

| | |
|---|---|
| PHA | Polyhydroxy alkanoates |
| PHB | Polyhydroxy butyrate |
| PHBV | Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) |
| Phen. resin | Phenol formaldehyde resins |
| PLA | Polylactic acid |
| PM | Particulate matter |
| POP | Persistent organic pollutants |
| PP | Polypropylene |
| PRTR | Pollutant Release and Transfer Register |
| PTT | Polytrimethylene terephthalate |
| PS | Polystyrene |
| PUR | Polyurethane |
| PVC | Polyvinylchloride |
| RAS | Asia and the Pacific |
| SBR | Styrene-butadiene |
| SOx | Sulphur oxide |
| SUP | Single Use Plastics |
| t | Tonne |
| TPS | Thermoplastic starch |
| TRL | Technology readiness level |
| UNEP | United Nations Environment Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| UF | Urea-formaldehyde |
| VCM | Vinyl chloride |
| VOC | Volatile organic compound |
| WEEE | Waste electrical and electronic equipment |

# Summary

Greenhouse gases (GHGs) are released throughout the lifecycle of plastics, from the extraction of their base resources, through the refining and processing of these into plastics and the conversion of plastics into products and components, to the products' use phase and then their end-of-life pathway, including incineration.

On top of climate impact, plastics also impact the environment and the world's natural capital in various and indirect ways, by consuming the natural resources stock and negatively impacting the world's ecosystems, such as soil, land, air, water and living organisms.

In light of the current rising trends in the consumption and production of plastics, systematic and integrated perspective on plastics and the carbon cycle is needed. Against this background, finding a way to make plastics compatible with a low-carbon economy is an urgent challenge and various opportunities have been identified to reduce the carbon intensity of the plastics system. One of the key challenges, however, seems to be the development of a knowledge base of the unintended side effects of how plastics and plastic products are managed.

To reinforce the understanding of the links between (the circularity of) plastics and climate change and to provide insights to inform future discussions on the potential (and limitations) of circular plastics and the corresponding impacts on climate and natural capital, the European plastic value chain, from the extraction of raw materials through production and use to the end-of-life waste treatment of plastics, was analysed from a lifecycle perspective. The focus of this analysis is the impact of all steps in the total plastics value chain across Europe, including feedstock production, refining, cracking, compounding, manufacturing and waste management. Because of the diversity of plastics and the number of applications in which they are used, the impacts of the use phase are not included.

The total greenhouse gas emissions caused by the plastics value chain, for the plastics volume converted in the European Union (EU) in 2018, is estimated at 208 million tonnes (Mt) of carbon dioxide equivalent ($CO_2$-eq). The majority, 63 %, of the greenhouse gas emissions in the EU plastics value chain are caused by its production. Converting these polymers into products accounts for 22 %, and plastic waste treatment at end-of-life adds another 15 %, mainly due to incineration.

There is considerable variability among specific plastics in greenhouse gas emissions during their lifetimes, depending on the polymer type and production technique. Overall, however, when 1 kilogramme (kg) virgin fossil-based plastic product comes onto the market, it has already caused at least 2.9 kg of greenhouse gas emissions. Moreover, the same product will cause a further 2.7 kg of emissions[1] when it is discarded and if it is incinerated.

The share of biobased polymers is very small compared to the fossil-based plastics – in 2019, their total global production was 3.8 Mt, around 1 % of the total production volume of fossil-based polymers. The biobased plastics value chain has the potential to reduce carbon dioxide ($CO_2$) emissions due to biogenic/sequestered $CO_2$ if the usage of biobased plastics were to increase significantly and if biobased plastic waste were recycled rather than incinerated. As for fossil plastics, decarbonisation of the energy-related emissions plays a crucial role in reducing $CO_2$ emissions from bioplastics value chains. The land-use change-related direct and indirect impacts on greenhouse gas emissions, which can significantly alter bioplastics' overall potential for reducing greenhouse gas emissions when compared to fossil-based plastics, are commonly not included.

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[1] Not taking into account avoided emissions because of energy recuperation

A scenario calculation (2), substituting all fossil-based plastics with biobased ones in the EU, resulted in overall greenhouse gas emissions of 146 Mt of $CO_2$-eq in total for biobased plastics yearly, 30 % less than the emissions of 208 Mt of $CO_2$-eq from the fossil-based value-chain.

Both fossil-based and bioplastics have implications for several natural capital assets throughout their entire lifecycles, such as the depletion of natural resources, water and air pollution, land use and soil erosion and loss of biodiversity. Biobased plastics are based on various feedstocks and can have a variety sustainability impacts on land and water use, biodiversity, indirect greenhouse gas emissions and create competition with food production. The overall impacts of biopolymers need to be thoroughly evaluated case by case.

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[2] Excluding (i-)LUC impacts and the same waste treatment scenario as the current situation

# 1 Introduction: plastics in a circular economy

## 1.1. Background

In recent years, plastics in the environment has become an important issue in both European and global environmental debates and policy, especially its predominantly linear pattern of production and consumption, and its striking leakages particularly into the marine environment.

Plastics have become a prominent feature of EU policymaking leading to, amongst others, the revision of several Directives, the adoption of a Directive specifically on (single-use) plastics, and a specific EU Strategy for Plastics in a Circular Economy ([3]). The von der Leyen Commission (2019-2024) plans to make the EU a leader on the issue of single-use plastics. In the European Strategy for Plastics in a Circular Economy (EC, 2018) the European Commission highlighted that plastic is an important and ubiquitous material in the EU's economy and its citizens' daily lives, but also stresses the urgent need to tackle its related environmental problems because of the way it is currently produced, used and disposed. More recently, the EU 2020 New Circular Economy Action Plan ([4]) emphasised action to increase circularity and reduce the environmental impacts of plastic with particular focus on micro-plastics, requirements for packaging and bio-based and biodegradable plastics.

The objectives of the European Green Deal (EC, 2019) affect the plastic value chain, for example by setting specific goals for the reduction of greenhouse gas emissions, both in the short and long term, and reinforcing all packaging in the EU market, including plastic packaging, being reusable or recyclable in an economically viable way by 2030. In addition, the Green Deal proposes measures on microplastics, a policy framework on bio-based and compostable plastics, and a timely implementation of the Single Use Plastics (SUP) directive.

## 1.2. Plastics and the environment in a circular economy

A forthcoming EEA report on plastics in a circular economy describes the diverse appearance and widespread use of plastics in society and explores the main challenges involved in transitioning towards a circular plastics economy (EEA, 2020d). It assesses the overall environmental impacts that occur across the lifecycle of plastics, including the leakage of plastics into the natural environment as well as the growing demand for fossil resources (such as oil and gas) and related emissions of greenhouse gases. Finally, it shows that an increasing number of EU initiatives are under way but that more coordination and scaling up is needed to ensure a persistent, longer-term move towards a sustainable and circular plastics system.

## 1.3. Focus on greenhouse gas and natural capital implications of plastics (including biobased plastics)

In 2019, the carbon footprint of global plastic production and incineration was estimated at 850 Mt of $CO_2$ (CIEL 2019). Taking into account the currently planned growth in plastic production and use worldwide, these emissions could reach 1 340 Mt by 2030 and 2 800 Mt by 2050. Based on production volumes, the EU's contribution to this global impact could be 15 to20 % (CIEL 2019).
In 2018 the total annual global emissions of greenhouse gases were estimated by the International Panel on Climate Change (IPCC) to be 55.3 gigatonnes (Gt) $CO_2$-eq (UNEP 2019), of which plastics contributed about 1.5 %.

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[3] https://ec.europa.eu/environment/waste/plastic_waste.htm

[4] https://ec.europa.eu/environment/circular-economy/

Greenhouse gas emissions are released all along the lifecycle of plastics, during the extraction of the resources, their refining and processing, the conversion of plastics into products and components, the use phase and the products' after-use pathway, including incineration.

On top of the carbon issue, plastics also impact the environment and the world's natural capital in various and indirect ways, by using and impacting the planet's stock of natural resources, including geology, soil/land, air, water and living organisms.

In light of the current rising trends in the use of plastics, systematic and integrated perspective on plastics and the carbon cycle is needed. Against this background, finding a way to make plastics compatible with a low-carbon economy is an urgent challenge and various opportunities have been identified to reduce the carbon intensity of the plastics system. One of the key challenges, however, seems to be the development of a knowledge base of the unintended side effects of how plastics and plastic products are managed.

## 1.4. Goal and scope

The overall goal of this report is to reinforce the understanding of the links between different phases of the plastics value chain and climate impacts, and provide insights to inform future discussions on the potential (and limitations) of circular plastics and the corresponding impacts on climate and natural capital. This is done from the perspective of a material, plastics, from the extraction of raw materials through production to the end-of-life waste treatment of plastics ([5]). Most existing studies on climate impacts of plastics focus solely on the production of plastics (from raw material to plastic (product)) or on waste management aspects (from collection, over sorting to valorisation (recycling/incineration). Analyses on product level, on the other hand, mostly include both production, use and end-of-life management, but primarily focus on one product, and mostly not on the total market.

The current report provides insights on climate impacts for one specific year, being 2018, of both the production of plastics in the EU and the management of European plastic waste.

The key benefit of this approach is that it considers potential burden shifting from one stage of the lifecycle to others that might be beyond the (geographical) scope of the report. This approach can be applied both at the level of a product, such as a car or a packaging, a societal functionality, such as mobility and heating, or a material, such as plastics.

In this report focus is on plastics produced in Europe but because of the diversity of plastics and the number of applications in which they are used, the impacts of the use phase are not included. The focus is on the impacts of all steps in the total plastics value chain in EU Member States, including feedstock production, refining, cracking, compounding, manufacturing, waste management, excluding the use phase.

The report is concerned with the European plastic system, including both direct and indirect impacts, so impacts outside the EU but related to plastics consumption in Europe, from resource use and production to end-of-life management of EU plastics waste wherever they may occur are included. This will provide a general overview of the size of the impacts of each step in the value chain, and how each step contributes.

The report uses the overall carbon footprint of the European plastic system, which is a global measure of the greenhouse gas emissions over the entire European plastic value chain from oil extraction to waste management and includes contributions of all incoming and outgoing mass and energy flows.

The analysis distinguishes between:

- direct emissions: emissions emitted directly during the various foreground processes;

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[5] This materials perspective differs by definition from a product and the functionality perspective

- indirect emissions: those emissions emitted during the production and transport of materials or the energy used in the various background processes – for example, during the production of electricity that is used in the plastic production, regardless whether these processes occur in or outside the EU;
- avoided emissions: for waste management purposes, it is key to include avoided emissions as well to account for the benefits of the produced output streams of the waste management process (JRC 2011). These avoided emissions are emissions that are considered to be avoided because of the valorization of an output flow from waste processes, thereby avoiding the traditional production of a similar product and the associated emissions. In the current report, avoided emissions for energy recuperation during incineration are included explicitly. For recycling, these avoided emissions are included implicitly as recycling plastics decreases the demand of virgin feedstock materials (provided that the plastics are both recycled in Europe and the recyclate is used as a feedstock in Europe).

Chapter 2 quantifies the greenhouse gas emissions of the European plastics system. Chapter 3 focuses on bioplastics and their effects on greenhouse gas emissions, based on available information from relevant case studies. In Chapter 4, natural capital implications of plastics and bioplastics are described.

### 1.5. Limitations of the report

The current report has its limitations, both with respect to the approach and the scope. For reasons of clarity, these limitations are listed explicitly:

- the report does not claim to provide a complete or partial life cycle assessment, nor to follow any official assessment procedure or standard;
- the reported greenhouse gas emissions always refer to a combination of direct, indirect and avoided emissions, regardless the place where these emissions occur; so they should be considered as global emissions;
- analyses of uncertainty and sensitivity have not been performed.

Although this report provides general insights in the link between plastic management and greenhouse gas emissions, it would benefit from complementary studies and reports providing additional insights in one or more specific aspects of the emission of greenhouse gasses during the life time of plastics or to look at it from an alternative perspective. These specific aspects could relate for example to a specific life cycle stage (such as resource extraction and the role of shale gas as resource for plastic production), a specific polymer (such as PUR), a specific product (such as packaging), a specific sector or a functionality (such as transport or mobility). Or these could focus more on the production perspective by diving deeper into the contribution of the processing of resources or the conversion of polymer into products, or on the consumers perspective focussing on the role and responsibility of consumers in the management of plastics such as during the collection of plastic waste fractions.

Also more methodology related issues could be further elaborated to generate additional insights on the environmental impact of the plastics value chain such as the link with existing greenhouse gas emission inventories, the contribution of littering and microplastics to greenhouse gas emissions and natural capital implications, the impacts of indirect land use change and/or other environmental issues (such as acidification, eutrophication, …).

# 2 EU plastics value chain and greenhouse gas emissions

### Summary and discussion

The total greenhouse gas emissions caused by the plastics value chain, for the plastics volume converted in the EU, is estimated at 208 Mt $CO_2$-eq per year (Table 2-1). This figure is the result of a bottom-up approach, taking account of all emissions over the whole lifecycle, from resourcing to waste processing, and taking into account both direct and indirect emissions. The resulting figure is therefore higher and gives a more complete view for the plastics value chain compared to the figures reported, for example, in the EU greenhouse gas emissions inventory, in which the plastics value chain is integrated in the sectors 'Petroleum refining' (111 Mt $CO_2$-eq in 2018) and 'Chemicals' (73 Mt $CO_2$-eq in 2018).

It has been estimated by Zheng and Suh (2019) that the global plastic production was 380 Mt in 2015 producing emissions of 1.8 Gt of $CO_2$-eq. The total plastics production in Europe in 2018 was 61.2 Mt, which is around 16 % of the total global production – 16 % of the Zheng and Suh (2019) figure of 1.8 Gt $CO_2$-eq for 2015 is approximately 285 Mt $CO_2$-eq.
The total greenhouse gas emissions in the EU in 2018 were 3.9 Gt $CO_2$-eq (EEA 2020b).

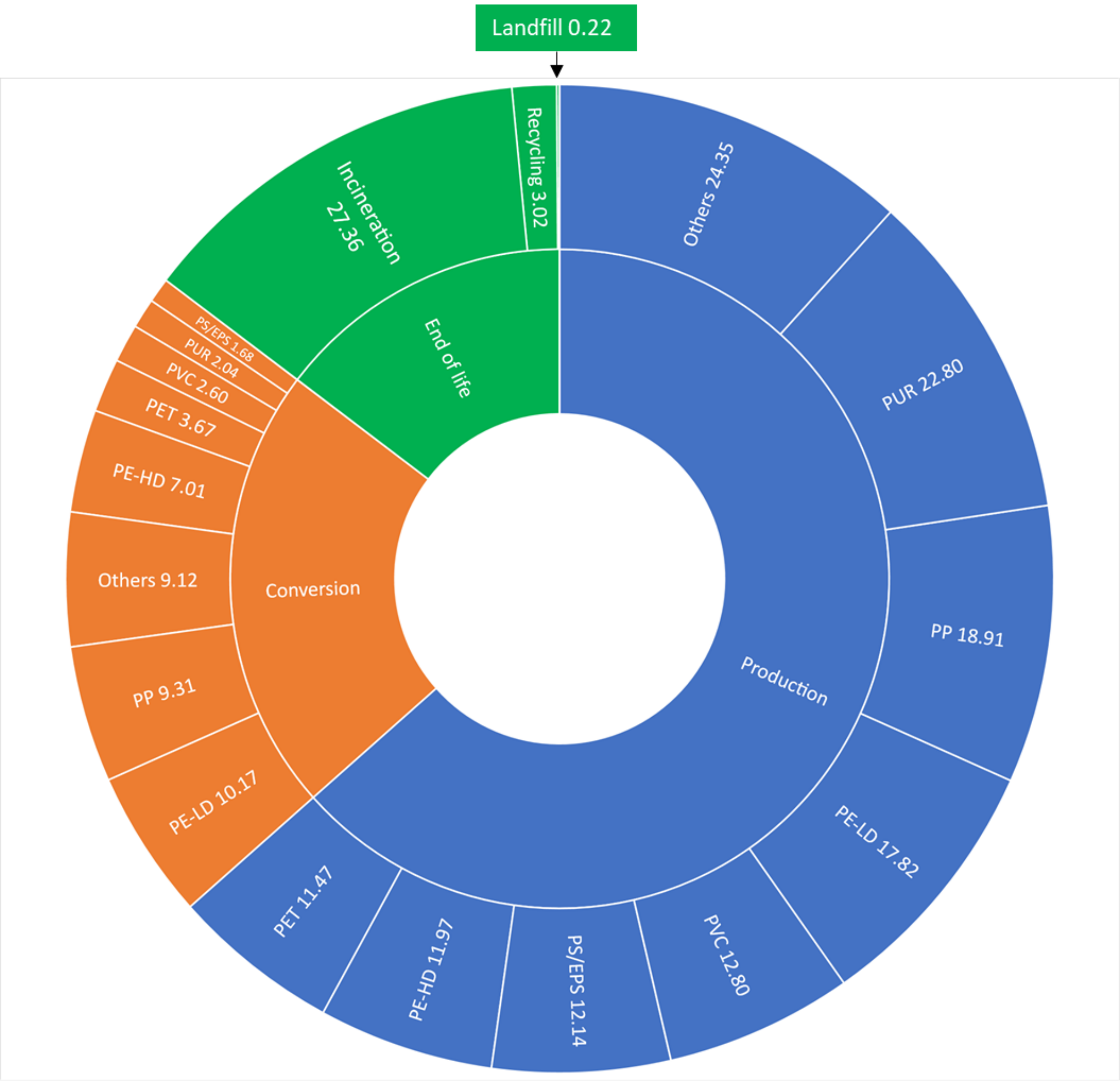
*Table 2-1 Estimated annual greenhouse gas emissions from EU and global plastics value chains*

| **Stage** | **Category** | **EU estimate (Mt $CO_2$ eq) (own calculation)** | **Global estimate (Mt $CO_2$ eq) (Zheng and Suh, 2019)** |
|---|---|---|---|
| **Production** | PP | 18.91 | 134.84 |
| | LD PE | 17.82 | 125.57 |
| | HD PE | 11.97 | 101.35 |
| | PVC | 12.80 | 78.51 |
| | PUR | 22.80 | 132.30 |
| | PET | 11.47 | 109.96 |
| | PS/EPS | 12.14 | 87.93 |
| | PP&A fibers* | | 213.88 |
| | Additives* | | 55.00 |
| | Others | 24.35 | 45.39 |
| **Conversion** | PP | 9.31 | 92.89 |
| | LD PE | 10.17 | 69.63 |
| | HD PE | 7.01 | 58.40 |
| | PVC | 2.60 | 22.53 |
| | PUR | 2.04 | 32.18 |
| | PET | 3.67 | 26.66 |
| | PS/EPS | 1.68 | 31.00 |
| | PP&A fibers* | | 159.30 |
| | Additives* | | 25.90 |
| | Others | 9.12 | 16.58 |
| **End of life**** | Recycling | 3.02 | 49.25 |
| | Incineration | 27.36 | 95.96 |
| | Landfilling | 0.22 | 15.59 |
| **TOTAL** | | 208.44 | 1,780.46 |

**Notes:** * Zheng and Suh (2019) include additives and polyester, polyamide and acrylic fibres, which are not included in this report
** reported number do not include any avoided emissions, and only relate to direct and indirect emissions during the end of life phase

Sixty-one per cent of the greenhouse gas emissions in the EU plastics value chain occur in the production phase. Converting these polymers to products accounts for 21 %, and plastic waste treatment adds a further 18 %, mainly due to incineration (Figure 2-1).

*Figure 2-1 Total greenhouse gas emissions from the EU plastics value chain, 2018, Mt $CO_2$eq per year*



**Source**: ETC/WMGE, 2021

It is clear that emissions reported by large refineries and resin production sites only cover part of the total greenhouse gas emissions related to the plastics value chain. A significant part of the these emissions also come from conversion activities, which usually take place in a variety of smaller companies, scattered over the EU. The end-of-life phase is also responsible for a significant share of the emissions, which are instantaneously emitted from incineration facilities or released from landfills over time.

## 2.1. Introduction

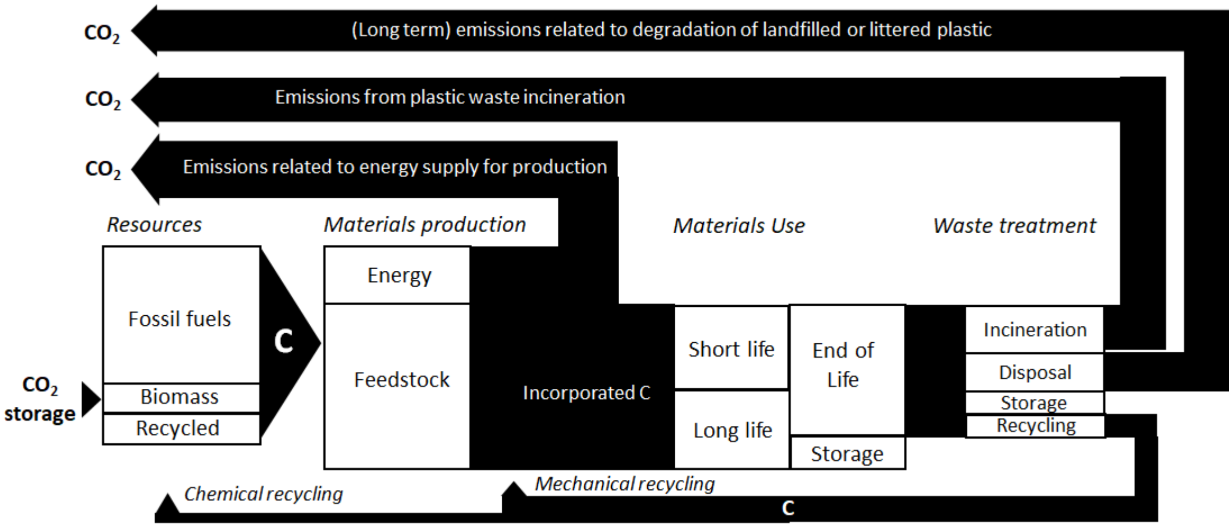
Nearly every piece of plastic begins as a fossil fuel, and greenhouse gases are emitted at each stage of a plastic's lifecycle. Emissions occur:

1) during fossil fuel extraction and transport;

2) in the production phase, which can be divided in two important steps: the production of the polymers (plastic materials) and the conversion of these polymers into (intermediate) products;
3) in the use phase, where plastics products become part of a plastic stock; and
4) in the end-of-life-phase, when plastic waste is either littered or sent to incineration, recycling or a landfill.

Greenhouse gas emissions are not only caused by the energy or fuel consumed during production, conversion, use, transport, etc. In addition, plastics as such have a large amount of carbon embedded in them, which is only released into the atmosphere at their end of life, when they are incinerated (immediate emission) or landfilled/littered (partly released over time). Thus, all plastics' embedded carbon has the potential to be released as $CO_2$. Recycling offers the opportunity to keep the embedded carbon in the loop, while producing plastics from biomass avoids adding more fossil carbon to the loop (Figure 2-2).

*Figure 2-2 Overview of basic sources and sinks of CO2 in the plastics' product chain using a carbon flow accounting approach.*



**Note:** Arrows indicate storage (embedded carbon) and emissions (release of embedded carbon). Flows are not proportional to the width of the arrows.
**Source**: Adapted from Gielen (1998)

Greenhouse gas emissions are thus not limited to, for example, the on-site emissions measured at polymer production sites. They also include upstream and indirect emissions related to, for example, crude oil extraction or electricity production for the power required for the plastics production and conversion processes. As indicated in the previous paragraph, carbon embedded in plastic products should be taken into account, as it causes emissions in the end-of-life phase.

Very few attempts have yet been made to map material flows and related $CO_2$ emissions for the total plastics value chain. It is very complicated to track the fate of carbon-containing resources through feedstock and polymer production to a variety of plastic products with different lifetimes and end-of-life options.

In this report, greenhouse gas emissions related to the European plastics value chain are estimated using a bottom-up approach. The bottom-up analysis starts from plastic production, consumption and waste management data, with greenhouse gas emission factors then attributed to the flows of each lifecycle step, which then allow the calculation of the emissions throughout the value chain.

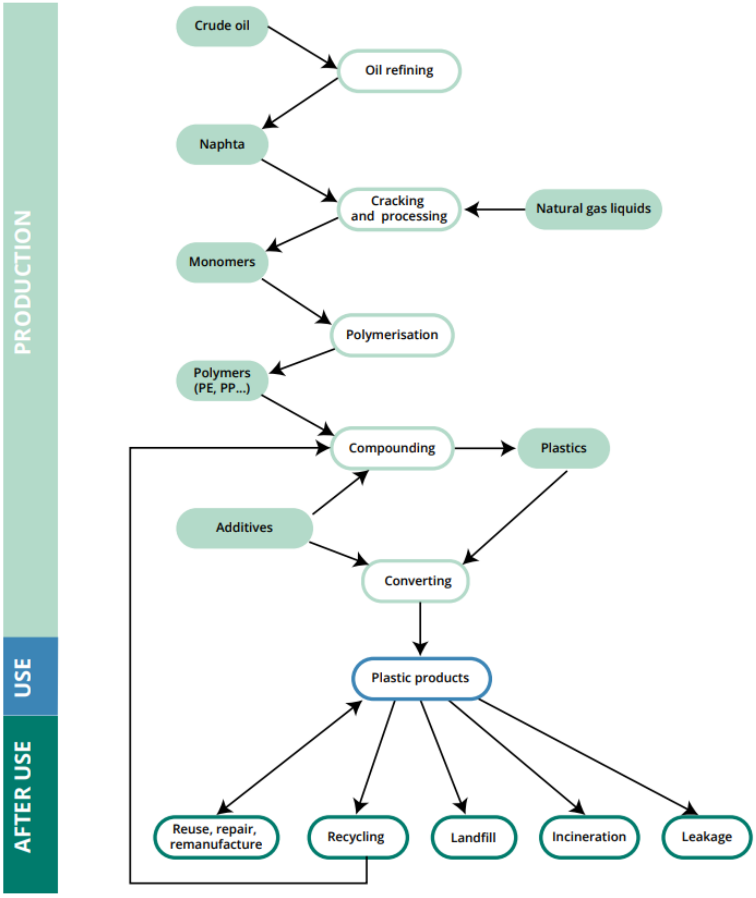
Greenhouse gas emissions are expressed assuming a 100 year time horizon for the cumulated integration of the IR (infrared radiation) of the emitted GHGs, applying the IPCC 2013 methodology ([6]). This means that not only $CO_2$ emissions, but also other greenhouse gases – methane, nitrous oxide, etc. – are included. These other greenhouse gases vary in their relative contributions to global warming. The difference is expressed by the global warming potential (GWP), which is a factor used to calculate the contribution of other greenhouse gases in terms of $CO_2$ equivalents.

## 2.2. Release of greenhouse gasses along the EU plastics value chain

### Material flows in the EU plastics lifecycle

The plastics value chain is both very diverse and globally spread. Oil and gas, which are still the principal feedstock for plastics production, are sourced in different parts of the world. Polymers are produced in the EU, not only for the EU market, but also for export, and imported. These polymers are converted into plastic products, which are sold in the EU, but again, also exported, and imported. Similarly, plastic products are sold on the EU market or exported to other markets, or imported. Finally, plastic waste, collected for recycling, is partially exported for processing outside the EU.

*Figure 2-3 EU plastics lifecycle*



**Source**: EEA (2020d)

Figure 2-4 summarises some key figures for material flows in the EU plastics value chain. The total primary production of polymers in the EU is estimated at 61.8 Mt per year. Polyethylene (PE) and polypropylene

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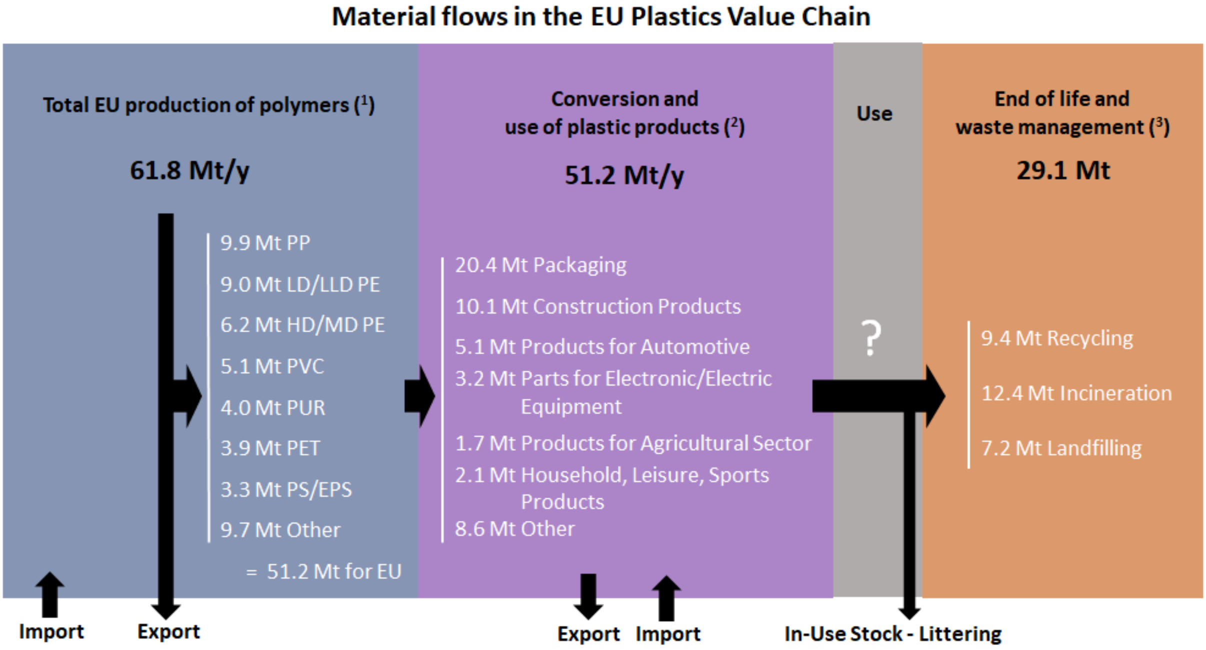
[6] See also https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials

(PP) represent by far the largest volume, followed by polyvinylchloride (PVC), polyurethane (PUR), polyethylene terephthalate (PET) and (expanded) polystyrene ((E)PS). The EU converters demand of around 51.2 Mt per year is smaller than polymer production, meaning that the EU is a net polymer exporter (Plastics Europe 2018). Packaging, building and construction, and the automotive sector use almost 70 % of all plastics in Europe, with the packaging sector alone accounting for almost 40 % of it.

There is, however, a gap between the volume of plastic used in products each year, 51.2 Mt, and the yearly volume of plastic waste collected, 29.1 Mt. There are several reasons for this imbalance. Firstly, plastic products have variable lifetimes: packaging becomes waste in a few days or weeks, whereas building products last for decades. Secondly, not all waste is collected properly; and finally, not all plastic products produced in the EU are sold, used and discarded in the EU itself.

*Figure 2-4 Production, conversion, and waste volumes in the EU plastics value chain, 2018, Mt per year*



*[1] EU 28+NO/CH total production volume, 2018 (Plastics Europe, Plastics, The Facts, 2019)*
*Production includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants and PP-fibers.*
*Not included: PET-fibers, PA-fibers and polyacryl-fibers.*
*[2] EU 28+NO/CH total converters demand, 2018 (Plastics Europe, Plastics, The Facts, 2019)*
*[3] Waste collection and treatment figures, 2018 (Plastics Europe, Plastics, The Facts, 2019)*

**Note:** Figures may not sum up due to rounding
**Source**: Plastics Europe (2018)

The analysis is somewhat complex, so in order to obtain a snapshot of the European plastics value chain and related greenhouse gases, the scope for this analysis was defined as follows.

- 2018 was the Reference year.
- The volume of polymers produced for the EU market equals the EU converters demand: 51.2 Mt per year. If converters import some plastic polymers from outside the EU, the carbon footprint of these is assumed to be the same as the carbon footprint of polymers produced in the EU. Greenhouse gas emissions related to energy use in the production and conversion steps are based on figures which reflect the average EU energy mix of fossil-based, nuclear and renewable energy.
- No impacts are allocated to the polymers produced in the EU and exported; similarly no (avoided) impacts are allocated to the use of secondary materials (recycled plastics);

- PET-fibers, PA-fibers and polyacryl-fibers are not included in the figures from Plastic Europe (2018), and also not included in our analysis. The European production of man-mad fibers is estimated by the European Man-Made Fibre Association at 3.5 Mt in 2018. (ETC WMGE 2021)
- The potential impact of plastic products made outside the EU but sold, used or discarded in the EU was not taken into account. In this simplified approach, the plastic conversion of 51,2 Mt per year in the EU was taken as plastic use. As will be explained further, no significant greenhouse gas emissions were allocated to the use phase.
- The greenhouse gas emissions in the end-of-life phase were based on plastic waste collection figures, 29.1 Mt: plastics collected for recycling, for example, were assumed to be recycled in the EU. Additional impacts from long-distance waste transport, for example, were not reflected in the result. It is, however, known from statistics on international trade (Comext), that 1.8 Mt of plastic waste were exported from the EU in 2018, mainly to countries in Asia (EEA 2019).

**Greenhouse gas emission intensity factors**

It is clear that existing greenhouse gas emission datasets do not provide a complete picture of emissions at the level of product or material value chains. In the following paragraphs, a bottom-up approach was therefore used. The basic data for this exercise are greenhouse gas emissions intensity factors that are found in lifecycle analyses and databases such as Ecoinvent ([7]). They express the level of emissions per (mass) unit produced, used, transported or treated (kg $CO_2$ eq per kg of material), including direct and indirect emissions per lifecycle phase. In this case, distinctions were made between:

- the production phase, including crude oil production, refining and polymer production;
- conversion;
- use;
- end-of-life and waste management

Resulting factors used in this report are summarised in Figure 2-5, and will be discussed in more detail in the following sections.

For the production and conversion phases, specific estimates can be made per polymer type. In this case, the primary focus was on high volume plastics, so common polymer types were distinguished: polypropylene, high- and low-density polyethylene, polyvinylchloride, polyurethane, polyethylene terephthalate and polystyrene. For other polymers, the median value of the others combined was used as an estimate.

Little is known about the emissions related to the use phase, but as discussed later, in general, greenhouse gas emissions in the use of plastics can be assumed to be insignificant.

For the end-of-life phase, no distinction was made between the fate of different polymer types. The three main routes considered for plastic waste are recycling, incineration and landfilling.

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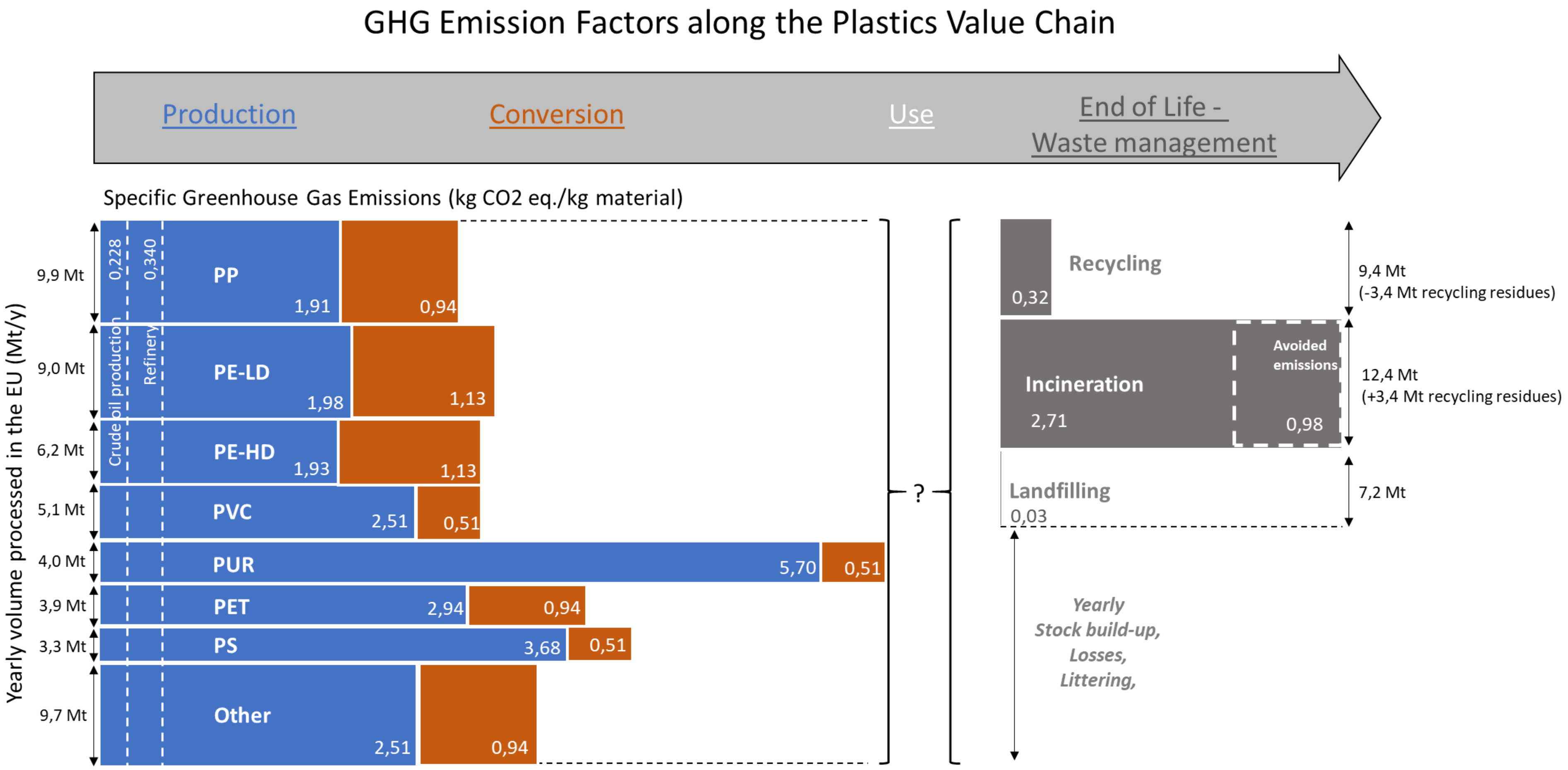
[7] https://www.ecoinvent.org/

*Figure 2-5* *Greenhouse gas emissions intensity factors (horizontal axis) and material flows (vertical axis) in the EU plastics value chain used in the bottom up analysis*



**Source**: ETC WMGE

Results show that, for plastic products, there is quite some variability in specific greenhouse gas emissions, depending on the polymer type and conversion technique. But overall, it can be concluded that, when a 1 kg plastic product comes onto the market, it has already caused at least on average 2.9 kg $CO_2$-eq emissions. Moreover, the same product will cause a further 2.7 kg $CO_2$-eq emissions when it is discarded and incinerated[8]. These emissions are the equivalent of travelling 25 and 23 kilometres respectively in an average European passenger car (EEA 2020b).

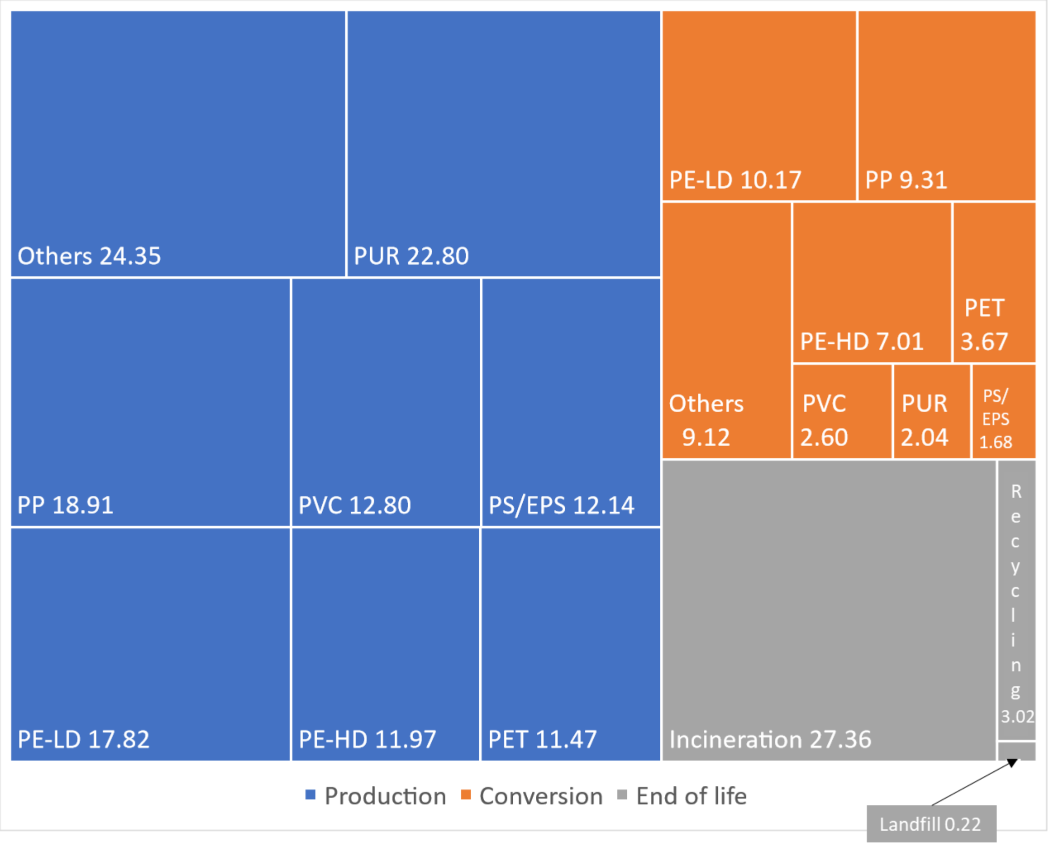
For the purpose of comparison, according to Materials Economics (2019),the carbon footprints for the primary production of a kilogramme of steel and aluminium are 1.9-2.4 and 12 kg $CO_2$-eq respectively.

**Quantification of greenhouse gas emissions**

To obtain total annual greenhouse gas emissions for the European plastics value chain, intensity factors were multiplied with mass flows obtained from sectoral data for polymer production and conversion, and waste processing. The overall greenhouse gas impact of the EU plastics value chain corresponds to 208 Mt $CO_2$-eq. Results are summarized in Figure 2-6 and discussed further in detail in the following sections.

As the total greenhouse gas emissions in the EU in 2018 were 3,893 Mt $CO_2$-eq (EEA 2020b), of which the EU plastics value chain contributes about 5.5 %.

*Figure 2-6 Greenhouse gas emissions from the EU plastic value chain, 2018, Mt per year*



**Source**: ETC WMGE

Figure 2-6 shows that the majority, 63 %, of greenhouse gas emissions caused by the plastics value chain are related to the production resins. Converting these into products accounts for 22 %, and plastic waste treatment adds a further 15 %, mainly due to incineration.

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[8] Not taking into account avoided emissions for energy recuperation

The following sections provide more details about the bottom up calculation of greenhouse emissions related to the different lifecycle phases of the value chain.

### *2.2.1 Resource extraction*

For fossil-based plastics, resource extraction corresponds to crude oil production, as the fossil-based value chain starts by default with the production of crude oil. This covers several activities, going from exploration, through drilling, development, production and extraction, to surface processing and transport to the refinery. Each of these activities causes emissions: direct emissions, like methane leakage and flaring; emissions from fuel combustion and energy consumption in the drilling process of drilling; and even emissions caused by land disturbance when forests and fields are cleared for well pads and pipelines.

There are very few comprehensive datasets covering lifecycle emissions from crude oil production. Masnadi et al. (2018) estimated the emissions from 8,966 oil fields in 90 countries, representing 98 % of 2015 global crude oil and condensate production. From this dataset, the **global** volume weighted average upstream carbon intensity (CI) was calculated to be 10.3 grams $CO_2$ eq/megajoule (MJ) crude oil. Using a heat value for crude oil of 42–47 MJ/kg ([9]), the global weighted value for crude oil production would be in the range of **0.432-0.484 kg $CO_2$/kg crude oil**.

When estimating the greenhouse emissions more specifically for the **European** plastics value chain, it is important to take account of the variable sources of crude oil and natural gas that are supplied to the European market. As shown in Table 2-2, these supplies come from many countries all over the world, with different production practices and corresponding carbon intensities, ranging from 0.03 kg $CO_2$/kg crude oil to 0.458 kg $CO_2$/kg crude oil. The average carbon intensity for the EU cracker capacity mix is estimated at **0.228 kg $CO_2$ emissions per kilogram of crude oil** ([10]), which is lower than the weighted global value calculated by Masnadi et al. (2018). This 0.228 kg $CO_2$ emissions per kilogram crude oil corresponds to the gasses emitted over a 2 kilometre journey an average European car (EEA 2020c).

Similarly, the upstream natural gas supply chain has branches worldwide. The average carbon intensity for the EU cracker capacity mix is estimated at 0.173 kg $CO_2$ emissions per kilogram of gas feedstock.

*Table 2-2 European upstream chain of crude oil and natural gas, supply share and emissions upstream from refinery according to provenance, 2010 (10)*

| **Crude oil** | | |
|---|---|---|
| **Country of origin** | **Emissions due to crude oil production (kg $CO_2$/kg crude oil)** | **Share (% of weight)** |
| Russia | 0.201 | 32.8 |
| Middle East, Azerbaijan, Kazakhstan | 0.291 | 22.9 |
| Norway, Denmark | 0.069 | 15.7 |
| Libya, Algeria, Angola | 0.289 | 11.1 |
| United Kingdom | 0.198 | 10.1 |
| Nigeria | 0.447 | 4.3 |
| Venezuela | 0.458 | 2.8 |
| Netherlands | 0.030 | 0.3 |
| | **Average, according to cracker capacity mix:**<br>**0.228** | |

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[9] https://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

[10] https://www.plasticseurope.org/en/resources/eco-profiles

| **Natural gas** | | |
|---|---|---|
| **Country of origin** | **Emissions due to gas production (kg $CO_2$ /kg gas feedstock)** | **Share (% of weight)** |
| Norway | 0.077 | 23.6 |
| Netherlands | 0.027 | 23.2 |
| Russia | 0.348 | 22.7 |
| Algeria, Qatar | 0.289 | 16.5 |
| United Kingdom | 0.153 | 7.6 |
| Germany | 0.146 | 6.4 |
| | **Average, according to cracker capacity mix:**<br>**0.173** | |

There are several reasons for the variability in greenhouse gas emissions during crude oil production – gas flaring (burning) practices have a considerable influence. If not economically saleable, gas is either flared, reinjected or vented – directly emitting methane. The estimated share of flaring emissions in the global volume-weighted average upstream carbon intensity is 22 % (Masnadi et al., 2018). Besides intentional venting and flaring, methane emissions also occur from leaks from the pipelines that transport the gas from production sites to the distribution system (US EPA, 2019). Venting and methane fugitive emissions are, however, poorly detected, measured or monitored, and therefore, estimates of their contribution remain highly uncertain.

Another important factor to keep in mind is that as oil and gas fields near total exhaustion, greenhouse gas emissions generally increase due to the use of enhanced recovery practices as more energy is needed to manage higher quantities of water to be cleaned or injected into the bedrock (Norwegian EPA, 2019). Finally, on-shore oil and gas extraction cause land disturbance and indirect greenhouse gas emissions as forests and fields are converted into oil fields and can no longer absorb $CO_2$ (CIEL 2019). No quantitative estimates were found for this.

The above data refers to the extraction of crude oil as a basis for the production of plastics. However, a variety of products is made from crude oil and gas, and it is not always clear how these relate or can be allocated to plastics. In the references used, such as Ecoprofiles from Plastics Europe, this allocation has already been done.

### *2.2.2 Refining and polymer production*

#### Refinery

Crude oil is a complex mixture of hydrocarbons together with impurities such as sulphur and some heavy metals. Oil refining aims to remove the non-hydrocarbon components and to split the crude oil into a series of specific fractions, based on their different boiling points, such as butane, diesel, gasoline, heavy gas, kerosene, naphtha, oil and residual fuel oil. The principal fraction used for the production of plastics is naphtha.

As with crude oil production, the carbon intensities of global refining vary. Operating characteristics of different refineries depend on the type of crude oil they process and the demand for different fractions – naphtha, gasoline, etc. The **global** volume-weighted average, as calculated by Jing et al. (2020), was 40.7 kg $CO_2$-eq per barrel or 7.3 g $CO_2$ eq/MJ. Using a heat value for crude oil of 42–47 MJ/kg (9), the volume-weighted value for oil refining would be in the range of **0.307–0.343 g $CO_2$-eq/kg crude oil**. It is estimated that refining activities account for 40 % of the emissions from the oil and gas supply chain, and 6 % of all industrial emissions (Jing et al., 2020). On average, more than 95 % of the global refining carbon intensity is generated by $CO_2$, and only 4 % plus by methane.

Plastics Europe used data from seven oil refineries and world data from International Energy Agency (IEA) statistics to compile the **European** eco-profile for naphtha (Plastics Europe 2005). To produce 1 kg of naphtha, it was estimated that approximately 1.1 kg of crude oil is used and greenhouse gas emissions were estimated at **0.340 kg $CO_2$-eq/kg naphtha**, which is in line with the global figure from Jing et al. (2020). For each location of refineries and crackers, the respective country specific electricity mix, including the respective pre-chains, was used instead of an average EU electricity mix.

For this report, the scope was limited to the refinery itself, including all major process units, energy and hydrogen supplied to the refinery as well as the upstream emissions related to natural gas and electricity consumed by the refinery.

Carbon dioxide, methane and nitrous oxide are significant of greenhouse gas emissions from refining activities. Fugitive methane emissions occur, for example, from process equipment leaks while methane flaring can occur due to safety concerns, such as equipment malfunctioning.

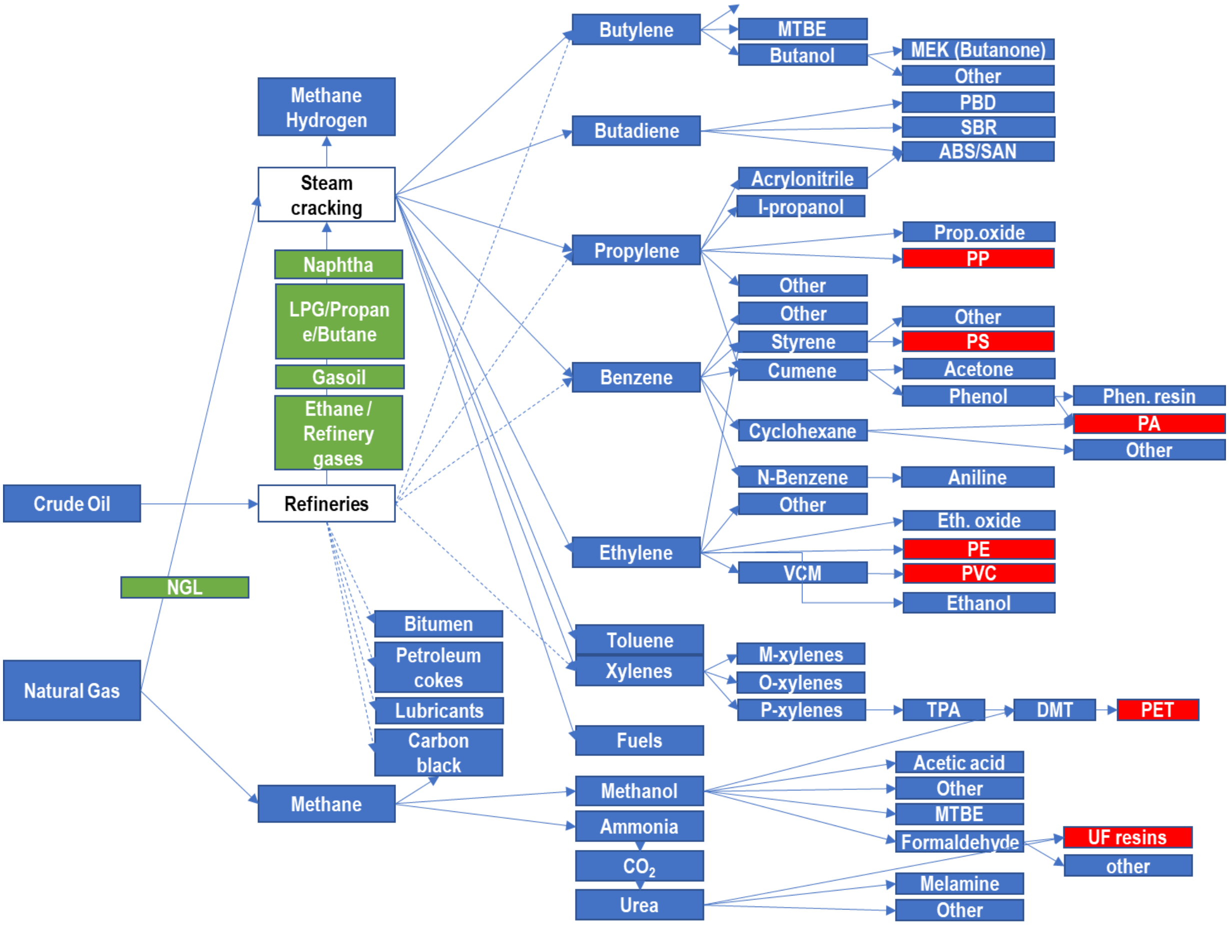
**Steam cracking and polymer production**

After refining, petroleum products are ready to be used as a feedstock for polymer production. The first step in the process is cracking through which complex organic molecules in petroleum products are broken down into simpler ones. Several methods exist, of which steam cracking is one of the most common and widely spread.

Steam cracking delivers a complex range of petrochemical intermediates, which are essential for the production of plastics (polymers), solvents, elastomers, fibres, fuel, etc. The main petrochemicals are ethylene, propylene, and methane. Their shares depend on the type of feedstock. Other important petrochemicals are butadiene and, in case of naphtha or gas-oil feedstock, pyrolysis gasoline with a high aromatic content.

Possible pathways from feedstock to polymer are illustrated in Table 2-7. Ethylene and propylene can be directly polymerised into polyethylene and polypropylene, or further processed into polyvinylchloride, polyethylene teraphtalate, polystyrene or polyurethane, for example. The processes are linked and highly integrated, which makes it difficult to allocate greenhouse gas emissions for the separate steps to the resulting polymer.

*Figure 2-7 Overview of a selection of processes and intermediates stages in the production of polymers and other petrochemical products.*



**Note:** Main cracker feedstock components are indicated in green. Main polymers are indicated in red
**Source**: Gielen (1998)

In the EU, the main feedstock for crackers is naphtha: together with condensates from natural gas production, the share of naphtha in European cracker feedstock is estimated at 74 % (Plastics Europe 2016). Other inputs are propane, butane and liquefied petroleum gas, 12 %; gas oil, 6 %; and ethane (refinery gases), 4 %.

Greenhouse gas emissions and other life cycle impacts related to polymer production are documented in Plastic Europe's Ecoprofiles, which were published from 2005 to 2017 (Plastics Europe 2016). The same data can be found in the Ecoinvent database, for which the last update, version 3.6, was released in September 2019 ([7]). These datasets provide figures for the production of a range of polymers, including all upstream processes. Due to the fact that for several unit processes, the data are aggregated, it is not possible to calculate greenhouse gas emissions for each of the steps in the production process separately. For most polymers, however, it is possible to trace some of the emissions hotspots in the process. The contribution of total electricity or heat use in production and upstream processes can also be estimated. Impacts related to electricity and/or heat use are tailored to the EU market by using the European energy mixes.

Resulting greenhouse emission figures for common polymers are listed in Table 2-3. They show that accumulated greenhouse gas emissions for the resource extraction, refining, cracking and polymer production stages range from **1.91 to 5.70 kg $CO_2$ eq/kg polymer** respectively for polypropylene and polyurethane rigid foam. As already stated, these values include emissions related to European electricity for cracking, polymerisation processes which take place in the EU, and world energy mixes for upstream processes such as crude oil refining. A more detailed description of the datasets is included in Annex 1.

*Table 2-3 Greenhouse emissions from polymer production, kg CO2eq/kg polymer*

| Polymer | Polymer production and key upstream contributing processes | Greenhous gas emissions (kg $CO_2$eq/kg polymer) |
|---|---|---|
| PP | Polypropylene, granulate production (Europe) | 1.91 |
| LD PE | Polyethylene, low density, granulate production(Europe) | 1.98 |
| HD PE | Polyethylene, high density, granulate (RER) production (Europe) | 1.93 |
| PVC | Polyvinylchloride bulk polymerised production (Europe) | 2.51 |
| PUR | Polyurethane, rigid foam production (Europe) | 5.70 |
| PET | Polyethylene terephthalate, granulate, amorphous production (Europe) | 2.94 |
| PS | Polystyrene, general purpose production (Europe) | 3.68 |

**Source**: Ecoinvent database, version 3.6 (7)

Finally, when multiplying the emission factors by the annual EU converters' demand – the amount of plastic resin needed for the production of plastic products in Europe – an estimate is obtained for the annual emissions due to polymer production in the EU plastics value chain. The calculation is illustrated in Table 2-4. For the "Other polymers"-category, in the absence of more specific data, the value for PVC was applied. This might be an underestimation, since these specialty plastics are more advanced and usually require several intermediate processes during production.

*Table 2-4 Estimated annual GHG emissions due to resource extraction, refining and polymer production in the EU plastics value chain, 2019*

| Polymer | Annual EU converters demand (Mt) (Plastics Europe, 2019) | Greenhouse gas emissions (kg $CO_2$-eq/kg polymer) (Ecoinvent 3.6) | Annual greenhouse gas emissions (Mt $CO_2$-eq) |
|---|---:|---:|---:|
| **PP** | 9.9 | 1.91 | 18.91 |
| **LD PE** | 9.0 | 1.98 | 17.82 |
| **HD PE** | 6.2 | 1.93 | 11.97 |
| **PVC** | 5.1 | 2,51 | 12.80 |
| **PUR** | 4.0 | 5.70 | 22.80 |
| **PET** | 3.9 | 2.94 | 11.47 |
| **PS/EPS** | 3.3 | 3.68 | 12,14 |
| **Others** | 9.7 | 2.51* | 24.35 |
| | | **TOTAL** | 132.26 |

**Note:** *Median value
**Source**: ETC/WMGE

Results show that the production phase for the polymers needed for further conversion in the EU causes emissions of approximately **132 Mt $CO_2$-eq**. More than 80 % of these emissions are related to seven polymers: high- and low-density polyethylene, polyethylene terephthalate, polypropylene, expanded polystyrene, polyurethane and polyvinylchloride.

### 2.2.3 Conversion

Plastic converters use the plastic resins – polymers, mixed with additives – to manufacture all kinds of plastic products and components. They use several different technologies, depending on the resin type and the type of product or application: injection moulding, blow moulding, calendaring, extrusion, foaming and thermoforming.

All of these techniques are used in a wide variety of companies, both large and small, producing a miscellany of products from drinks bottles and food packaging, through agricultural foils to plastics for textiles and components for electronic appliances or the automotive and aviation industries. Production volumes can vary from very small batches for specialised products to industrial-scale mass production.

The conversion step basically involves the application of mechanical and heat energy. Lifecycle inventory data for conversion processes show that the additional greenhouse gas emissions caused by these processes are in the range of **0.294–1.14 kg $CO_2$-eq/kg product** for the extrusion of plastic pipes and stretch blow moulding, respectively (Table 2-5). Electricity use represents 64 to 93 % of these emissions.

*Table 2-5 Greenhouse gas emissions from plastic conversion technologies (EU averages)*

| **Conversion technology and key contributing processes** | **Greenhouse gas emissions (kg $CO_2$-eq/kg product)** |
|---|---|
| Injection mould processing (Europe) | 0,962 |
| Electricity, medium voltage (Europe) | 0,62 (64%) |
| Heat, district or industrial, natural gas (Europe excluding Switzerland) | 0,22 (23%) |
| Blow mould processing (Europe) | 0,917 |
| Electricity, medium voltage (Europe) | 0,72 (78%) |
| Solid bleached board | 0,12 (13%) |
| Stretch blow moulding (Europe) | 1,14 |
| Electricity, medium voltage (Europe) | 1,06 (93% |
| Calendering, rigid sheets (Europe) | 0,322 |
| Electricity, medium voltage (Europe) | 0,21 (66%) |
| Steam, in chemical industry (Europe) | 0,07 (21%) |
| Extrusion of plastic film (Europe) | 0,416 |
| Electricity, medium voltage (Europe) | 0,28 (67%) |
| Heat, district or industrial, natural gas (Europe excluding Switzerland) | 0,03 (8%) |
| Waste plastic, mixture (Europe) | 0,03 (8%) |
| Extrusion of plastic pipes (Europe) | 0,294 |
| Electricity, medium voltage (Europe) | 0,21 |
| Heat, district or industrial, other than natural gas (Europe) | 0,05 |
| Polymer foaming processing (RER) | 0,513 |
| Electricity, medium voltage (RER) | 0,33 (64%) |
| Heat, district or industrial, other than natural gas (Europe) | 0,18 (36%) |
| Thermoforming with calendering (Europe) | 0,642 |
| Electricity, medium voltage (Europe) | 0,42 (66%) |

**Source**: Eco-invent database, version 3.6 (7)

Datasets which allocate certain conversion techniques to specific volumes of polymers in Europe are not available. Estimates can, however, be found in the literature for the share of conversion technologies used for the most common types of resin (Zheng and Suh 2019, Keoleian 2012) Using these estimates, some realistic assumptions were made regarding the shares of conversion technologies. GHG emission intensities were then calculated for the conversion of each polymer in the EU, by applying these shares on data from the Eco-invent 3.6 database (Table 2-6).

*Table 2-6 Estimated annual greenhouse gas emissions from polymer conversion in the EU plastics value chain, 2018*

| Polymer | Annual EU converters demand (Mt) (Plastics Europe, 2019) | Assumptions regarding conversion (adapted from Zheng and Suh, 2019) | GHG emissions (kg $CO_2$-eq/kg polymer) | Annual GHG emissions (Mt $CO_2$-eq) |
|---|---|---|---|---|
| **PP** | 9.9 | 74 % injection moulding; 24 % blow moulding; 2 % extrusion (pipes) | 0.94 | 9.31 |
| **LD PE** | 9.0 | 67 % injection moulding; 24 % blow moulding; 9 % extrusion (pipes) | 1.13 | 10.17 |
| **HD PE** | 6.2 | 67 % injection moulding; 24 % blow moulding; 9 % extrusion (pipes) | 1.13 | 7.01 |
| **PVC** | 5.1 | 51 % extrusion (pipes); 18 % calendering (sheets); 29 % injection moulding; 2 % blow moulding | 0.51 | 2.60 |
| **PUR** | 4.0 | 100 % polymer foaming | 0.51 | 2.04 |
| **PET** | 3.9 | 50 % injection moulding; 50 % blow moulding | 0.94 | 3.67 |
| **PS/EPS** | 3.3 | 100 % polymer foaming | 0.51 | 1.68 |
| **Others** | 9.7 | | 0.94* | 9.12 |
| | | | **TOTAL** | 45.60 |

**Note:** *Median value
**Source**: Plastics Europe (2019); Zheng and Suh (2019); Keoleian et al. (2012)

Results show that the conversion of polymers into plastic products in the EU emit approximately **46 Mt $CO_2$-eq**. Most of these emissions relate to the mechanical and heat energy needed for the conversion processes. These emissions correspond to 10 % of the 2018 worldwide greenhouse gas emissions caused by the combustion of car fuels (EEA 2020b).

### *2.2.4 Use*

For the vast majority of plastic products, it is impossible to allocate meaningful climate impacts to the use phase. Usually, plastic products do not cause any direct emissions during use and therefore only contribute in an indirect way to emissions caused by their usage. That is why the use phase is usually not taken into account in calculations, including in this report.

The focus of this report is material (carbon) flows. In the use phase, however, focus is on the product and its functionality. Plastics included in the product contribute to this functionality, but their contribution can vary in many ways. Specific greenhouse gas analyses or carbon footprint calculations for products or product groups typically do include the specific emissions from the use phase or the emissions upstream and downstream of it, but their purpose and approach differs from looking from the materials perspective. Therefore, the analysis does not include greenhouse gas emissions from products containing plastics.

To illustrate this, two totally different examples are discussed

- a polyethylene teraphtalate drinks bottle, with a short lifetime, made only of PET;
- a plastic component in a car, such as a dashboard, with a long lifetime, and composed of different plastic types.

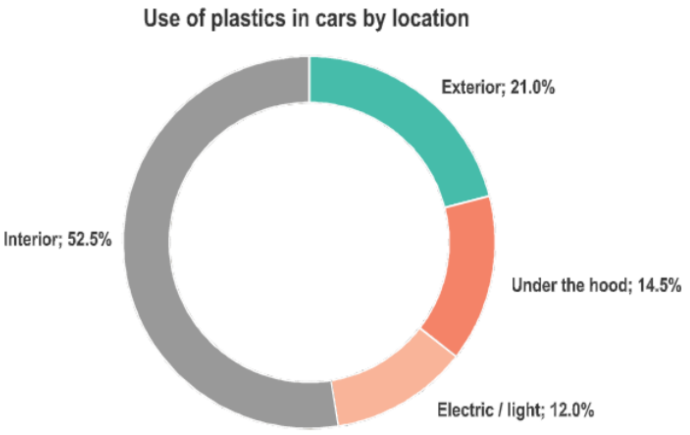
**Case example 1: polyethylene teraphtalate drinks bottle**

In the use phase, a polyethylene teraphtalate bottle provides the functionality of packaging for the drink it contains, and the packaging allows the drink to be transported and stored as needed. So, the only greenhouse gas emissions from the bottle during the use phase relate to the transport and other logistic activities, from the bottling plant to the retailer and from the retailer to the consumer. Additional emissions could be related to the energy needed to cool the bottle in a fridge. These impacts, however, can hardly be allocated to the plastic material, as they relate mainly to the functionality of providing and storing a drink rather than to the packaging itself.

**Case example 2: plastic car components**

The complexity of plastics used in applications is illustrated by cars. According to Kaartinen (2020), the composition and volumes of plastics in end-of-life vehicles vary a lot but newer ones typically contain more. The amount of plastics in end-of-life vehicles has been estimated at 13–25 % by mass, depending on the age of the car. In addition to plastics, vehicles contain ferrous and non-ferrous metals, fluids, electronics and other components. On average, approximately 105 kg of of a wide range of different polymers are used in a car. the main polymers are polypropylene, polyurethane, polyvinylchloride, acrylonitril-butadiene-styrene and polyamide/polycarbonate, but also polyethylene teraphtalate, polyamide, polycarbonate/ polybutylene terephthalate, polybutylene terephthalate, glass fibre reinforced polypropylene, etc., are used. Plastics are used in different car components ranging from exterior, interior and under-the-hood applications to electric devices, lights, etc. (Table 2-8). The complexity and heterogeneity of the plastic waste stream makes recycling end-of-life vehicles challenging. (Kaartinen, 2020)

*Figure 2-8 Plastics used in cars, location per cent*



**Source**: (Kaartinen et al. 2020b)

The main greenhouse gas impacts of a cars occur in the use phase, because of the fossil fuels consumed. However, as with a polyethylene teraphtalate drinks bottle, these impacts cannot be allocated to the plastics or other materials used in the car but relate to the function of transporting people or goods. Indeed, it could be argued plastics contribute to saving greenhouse gas emissions during the use phase of a car by replacing other, heavier materials such as metals in components. For every 100 kg reduction in the weight of a modern car, fuel consumption is reduced by approximately 0.2 litres per 100 km and results in greenhouse gas savings of 10 g per km (or 1 kg per 100 km).

These are just two examples to show that greenhouse gas emissions during the plastics use phase are very product-specific and cannot be related or compared to the emissions during the plastic (material) production or end-of-life (waste management) phases.

### *2.2.5 End of life – waste management*

The end-of-life/waste management phase covers all the steps after the use phase – the collection, incineration, landfilling or sorting and recycling into pellets or flakes ready for use in the production of new plastic products. As for the plastics themselves, it is quite misleading to talk about plastics waste as this can be very diverse, whether mixed with other materials or collected separately, limited to specific applications or consisting of several polymers.

The situation is actually quite complex when it comes to plastic waste and its management. For several applications (such as packaging waste, end-of-life vehicles, and waste electrical and electronic equipment) waste products are collected separately; they consist only of plastics or of plastics and other materials, and the plastic fraction can consist of various polymers. When we want to recycle these plastics, the respective polymers have to be sorted from the other materials; these polymer fractions are then subsequently recycled into flakes, regrind or agglomerate, ready for being used in new products; within each polymer fraction, the potential for being picked up by the market can depend on specific quality aspects, such as mechanical resistance, chlorine content, colour, density, etc. Additionally, plastics collected in mixed or residual waste may or may not be sorted further to separate specific polymers.

**Collection**

The first step in waste management, excluding waste prevention, is proper waste collection of either mixed or separated waste. Depending on the specific situation, collection and corresponding transport to the next processing step can differ significantly, from just a few to hundreds of kilometres. Compared to the rest of the plastics value chain, however, the greenhouse gas emissions related to waste collection and transport are very small. The average $CO_2$ emissions from the collection of waste by a specialised truck are about **0.0004 tonnes of $CO_2$/tonne kilometre,** so for a collection round of 40 km, the emissions per tonne of waste are 0.016 tonne $CO_2$. Emissions from the transport following collection to the disposal site are about five times lower at 0.00008 tonnes $CO_2$/tonne kilometre ([7]).

The main environmental impacts of waste collection and transport come from issues such as traffic congestion and local emissions of nitrogen oxides and fine particulate matter.

**Recycling**

As explained above, recycling is usually preceded by separate collection, sorting or pre-treatment, and several transport movements.

Table 2-7 gives an overview of the greenhouse gas emissions from the recycling for some commodity plastics in the EU, as reported by Deloitte and Plastic Recyclers Europe (2015) and Turner et al. (2015). The emissions from each step have to be added up to obtain a representative value for the recycling process itself. The recycling stage's total emissions range from 0.414 to 0.576 tonnes of $CO_2$ eq per tonne of waste, depending on the polymer type and mainly related to the energy (heat, steam, electricity) needed for the recycling processes.

These figures already take into account that both the sorting of the plastic waste and the reprocessing of the sorted waste lead to considerable amount of residues, that have to treated themselves once again and which are currently mainly incinerated. The share of residues of sorting and reprocessing plastic waste can be as high as 50 % of the input material, and typically amounts to on average between 20 and 50 %. (Antonopoulos, 2021)

*Table 2-7 Greenhouse gas emissions from plastic waste collection, sorting, transportation and recycling*

| **Waste management step** | **Greenhouse gas emissions (tonnes of $CO_2$-eq/tonne of waste)** | **Remarks** |
|---|---|---|
| Collection | 0.017 | Separate collection of plastic waste. Transport distances based on German averages.<br>(Plastics Recyclers Europe 2015) |
| Sorting/pre-treatment | 0.027 | Includes indirect emissions from dismantling and sorting of plastics from other recyclables in sorting facilities and may also include shredding and further sorting by plastic resin.<br>(Plastics Recyclers Europe 2015)<br>Sorting leads to 20% residues, going to incineration |
| Transportation to recyclers | 0.022 | (Plastics Recyclers Europe 2015) |
| Mechanical recycling | | Reprocessing sorted waste lead to 20% residues, going to incineration<br>Expressed as per ton output<br>(Plastics Recyclers Europe 2015) |
| PET recycling | 0.510 | |
| HD PE recycling | 0.348 | |
| LD PE recycling | 0.348 | |
| PP recycling | 0.348 | |
| PS recycling | 0.348 | |
| PVC recycling | 0.348 | |
| Others recycling | 0.348 | |
| **TOTAL** | 0.269-0.373<br>(0.321) | Min-max values for collection + sorting/pre-treatment + transportation + recycling (excluding treatment of residues), per ton plastic waste input<br>(average value) |

**Source**: Own calculation

If the recycling process leads to a secondary plastic (11) that can be used for the production of new products, this recyclate displaces virgin plastic on the market, reducing raw material extraction and production of virgin plastics and therefore leads to reduced greenhouse gas emissions. Based on the estimates discussed earlier, the avoided emissions from virgin polymer production from fossil resources could be 1.91–5.70 kg $CO_2$-eq/kg polymer. This is in line with other sources in the literature, which claim that recycling rather than incinerating plastic could reduce emissions by 1.1–3.0 tonnes $CO_2$ eq/tonne plastic compared to plastics from virgin fossil feedstock (EMF 2019).

Innovative recycling processes, such as chemical recycling, are in development and may have the potential of complementing mechanical recycling and incineration of plastic waste.

### Incineration

During incineration the embedded carbon in the plastic waste is completely oxidised to $CO_2$. Starting from a carbon content of plastic waste of about 0.75 tonnes of C/tonne of waste (IPCC 2006), the corresponding European greenhouse gas emissions are estimated to be 2.70 tonnes of $CO_2$-eq/tonne of plastic waste (Plastics Recyclers Europe 2015). Depending on the specific polymer, this carbon content, and the corresponding emissions when incinerated, can differ slightly. Adding 0.017 tonnes of $CO_2$-eq/tonne of

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[11] In this case an additional replacement factor based on quality ratio between recyclate and virgin material might be relevant

waste for collection before incineration (Table 2-8), the total emissions are estimated to be 2.71 tonnes of $CO_2$-eq/tonne of waste.

As this emission factor only concerns the direct emissions from incineration, the indirect emissions from production of all necessary auxiliaries for the incineration, such as energy and flue gas cleaning additives, have to be added. However, these indirect emissions are almost negligible compared to the direct emissions and are estimated at 0.05–0.10 tonnes of $CO_2$-eq/tonne of plastic waste (OVAM 2019).

As the energy content of plastic waste is generally recovered during incineration (as electricity, heat or both), the incineration process is credited for the benefits from avoided production of conventional energy (electricity and heat) replaced by energy recovered from plastic waste incineration. These avoided emissions are calculated based on EU average energy efficiencies for waste incineration of 13.7 % for electricity production and 31.8 % for heat recovery, and on EU average data for conventional electricity and heat production (as in the EU greenhouse gas emission inventory and the Ecoinvent database). (Nessi 2020b) (Nessi 2020a)
These credited or avoided emissions apply both to plastic waste sent directly to incineration and to sorting and reprocessing residues of plastic waste sent to recycling.

**Landfilling**

As plastic hardly degrades under natural circumstances, landfilling can hardly be regarded as an actual treatment option for plastics. Instead, it could/should be regarded as a way of temporarily storing, postponing the release of the carbon in the plastics. The fate of plastics in landfills is not fully understood and potential decomposition of plastics over hundreds of years might eventually lead to leakage of greenhouse gas emissions into the atmosphere. Legal or illegal fires on landfills can also lead to uncontrolled greenhouse gas emissions.

The EU has adopted a zero-landfill target to be achieved by 2030 for recyclable waste including plastics. The future options for plastic waste in the EU will therefore primarily be reuse, recycling or incineration. The available literature on greenhouse gas impacts of landfilling plastic waste gives a range of 0.004–0.010 tonnes of $CO_2$-eq/tonne of plastic waste (Deloitte and Plastics Recyclers Europe, 2015). Assuming a value of 0.01 tonnes of $CO_2$-eq/tonne of plastic waste, and adding 0.017 tonnes of $CO_2$-eq/tonne for the collection of the waste (see above), a value of **0.03** tonnes of $CO_2$-eq/tonne for the landfilling plastic waste can be assumed.

**Greenhouse gas emissions in the end of life – waste management phase**

Table 2-8 summarises the greenhouse gas emissions caused by the three main end-of-life options for plastic waste in the EU. In total, 46 Mt of greenhouse gases are emitted each year from plastic waste alone – this is an estimate based on the current waste collection and treatment practices. It is clear that only a fraction of the total carbon incorporated in plastic products that come on the market each year, is also released. As already indicated, each tonne of plastic has the potential to release 2.70 tonnes of $CO_2$eq when fully oxidised. So, it can be estimated that the total $CO_2$ incorporated in the 51.2 Mt plastics converted on the EU market each year is about 138 Mt $CO_2$-eq (2.70 x 51.2). Only 25 % of this potential is thus effectively emitted. This is due to the fact that many plastic products have long lifetimes and are stored in the “urban mine”. On the other hand, only 43 % of the plastics that reach their end of life are incinerated. For the other 57 %[11], immediate emissions are avoided through recycling bringing the carbon back into the loop, or landfilling, which stores carbon for the long term.

*Table 2-8 EU estimated annual greenhouse gas emissions from plastic waste management*

| **EoL option** | **Annual EU Plastic Waste treatment (Mt) (Plastics Europe, 2019)** | **Greenhouse gas emissions (kg $CO_2$-eq/kg polymer)** | **Annual greenhouse gas emissions (Mt $CO_2$-eq)** | **Avoided emissions (Mt $CO_2$-eq** |
|---|---|---|---|---|
| **Recycling** | 9.4 | 0.32 | 3.02 | -[12] |
| **Incineration** | | | | |
| **direct** | 12.4 | 2.71 | 33.60 | -12.11 |
| **recycling residues** | (3.4) | 2.71 | 9.17 | -3.30 |
| **Landfilling** | 7.2 | 0.03 | 0.22 | - |
| | | **Subtotal** | 46.01 | -15.41 |
| | | | **TOTAL** | **30.59** |

**Source**: ETC WMGE

### 2.2.6 Leakage of plastic waste to the environment/plastic waste degradation

Unmanaged plastic waste ends up in the environment. Annual plastic losses and littering worldwide in 2015 have been estimated by Ryberg et al. (2019) as 9 Mt, 2 % of the global production volume of 389 Mt. Losses occur throughout the entire lifecycle, but primarily in the use and end-of-life phases.

At present, the climate impacts of degrading plastic in the environment are not well understood due to the fact that studies are still in their early stages. Royer et al. (2018), however, have demonstrated that plastic waste on the surface of waterways continuously release greenhouse gases, especially methane, and the emissions increase as the plastic degrades.

Exposure to light seems to trigger the production of greenhouse gases, but the degradation of plastic once initiated seems to continue even in the absence of sunlight. The methane emissions ranged from 10-4 100 picamoles per gram per day and ethylene emissions ranged from 20-5 100 picamoles per gram per day. Even though the emissions per gram are low, taking account of estimates for overall quantities of plastic waste, Royer et al. (2018) produced a rough estimate that, globally, the annual emissions in 2015 from plastic waste pollution was 51 Mt of ethylene and 76 Mt of methane. For the methane alone, this is more than 2 100 Mt of $CO_2$eq (100 year global warming potential). They also estimate that, according to estimates of increasing production, by 2025 emission rates will increase by 33–36 %. Approximately 1 % of marine plastic waste is on the surface, while 99 % is below surface and emissions that not yet been studied.

Earth's oceans are an important natural greenhouse gas sink. Since the early 19th century, the oceans have absorbed 30–50 % of the $CO_2$ generated by humans. Microplastics in the oceans have on effect on how they are able to absorb and sequester $CO_2$ as microplastics interfere with the microscopic plants' (phytoplankton) and animals' (zooplankton) capacity for fixing carbon through photosynthesis or acting as biological carbon pumps. This describes their ability to capture $CO_2$ on the ocean's surface and transport it deeper into the ocean, thus reducing its release back into the atmosphere. Microplastics have also been shown to affect phytoplankton's ability to reproduce, slower their metabolic rates and affect the survival of zooplankton as they transfer the carbon to deeper into the ocean. (M. Shen et al. 2020) It is also unknown how the previously absorbed gases will behave and if they will further increase the atmospheric

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[12] As recycling plastics decreases the demand of virgin feedstock materials, the benefit of recycling is already included as in the actual demand of plastics, provided that the plastics are both recycled in Europe and the recyclate is used as a feedstock in Europe

build-up of $CO_2$. The degradation and breakdown of plastics was, until recently, an unrecognized source of greenhouse gas emissions, which are expected to increase as plastic production increases.

# 3 Biobased plastics value chain and greenhouse gas emissions

## Summary and discussion

**Overall biobased plastics value chain**

In 2019, the total global production of bio-based polymers was 3.8 Mt, around 1 % of the total production volume of fossil-based polymers. (European Bioplastics, 2018, market data) The share is very small compared to the fossil-based plastics.

The bio-based plastics value chain has further potential to reduce $CO_2$ emissions due to biogenic/sequestered $CO_2$ if their usage were to increase significantly and if bio-based plastic waste were recycled rather than incinerated. As for fossil-based plastics, the energy related emissions play a crucial role in reducing $CO_2$ emissions of biobased plastics value chains. The land-use change related direct and indirect impacts on greenhouse gas emissions, which can significantly alter biobased plastics' overall potential of reducing emissions when compared to fossil-based plastics, are commonly not included in lifecycle analyses.

Biobased plastics value chains are complex and their $CO_2$ footprints vary a great deal depending on the feedstock, its production and the target biopolymer, the production and utilisation of side and waste streams and different end-of-life options. Specific attribution of industrial greenhouse gas emissions to bio-based plastic production is challenging. With bio-based materials, the way that the biogenic carbon is calculated and where carbon credits are credited affects the overall emissions of the value chains. Challenges lie in the allocation of benefits in lifecycle analyses and the avoidance of double counting: the benefits of $CO_2$ uptakes plants plant and the benefits of incineration or composting as biogenic $CO_2$ is emitted need to be approached in a consistent and clear way.

With respect to data availability, case study-based data is mainly available for the bio-based plastics value chain.

The literature review study by Spearling et al. 2018 concluded that the overall global warming potential (GWP) was in the range of -0.3–11.9 kg $CO_2$-eq/kg for biobased plastics while Plastics Europe has reported a GWP range of 1.6–6.4 kg $CO_2$-eq/kg for fossil-based plastics. For this study, the literature review concluded that the greenhouse gas emissions of bio-based plastics are in the range of -4.9–11.9 kg $CO_2$-eq/kg of material. Negative emission results can imply for example that the emissions of bioproducts were considered, or release of biogenic carbon at end-of-life was not accounted for.

Based on existing studies, biobased plastics could potentially save 241–316 Mt of $CO_2$ eq. annually when substituting about 67 % of global plastic demand. Zheng et al. (2019) estimated that the global plastic production in 2015 (380 Mt) caused 1.7 Gt $CO_2$-eq of total life cycle emissions. The total plastics production in Europe in 2018 was 61.2 Mt, which is around 16 % of the global production; 16 % of the Zheng et al. (2019) figure of 1.7 Gt of $CO_2$-eq is approximately 272 Mt of $CO_2$-eq.

Scenario calculations in this study, based on the boundary conditions described and where all fossil-based plastics were replaced with bio-based plastics in Europe, resulted in overall greenhouse gas emissions from the EU's plastic demand of 146 Mt of $CO_2$-eq in total on a yearly basis, 30 % less than the emissions of 208 Mt from the fossil-based value chain calculations used in this study.

**Feedstock production**

Biobased plastics are made from renewably sourced raw materials mainly from carbohydrate rich agro-based sources, like corn or starch, and non-edible lignocellulosic feedstock, e.g. from wood-based sources.

As plants grow, they sequester atmospheric $CO_2$ and release $O_2$. As long as the material is in use, the carbon is kept stored in the biobased material. The biggest variations in GHG emissions in different reviewed LCA studies resulted from the use of different raw materials. However, the effects of land-use are not typically included in the LCA studies of bioplastics due to the challenges of addressing the land-use impacts.

The direct- and indirect impacts of land-use can affect the overall GHG emissions of biobased plastics. In the CE Delft Bioplastics in a circular economy-report, they assessed that the indirect land-use change risk is rather small for wheat, sugar cane, maize, and sugar beet raw materials (maximum of 10 % of emission), and that for oil crops, the risk is significantly higher.

Especially forests are important carbon sinks. Negative impacts can relate to the sourcing of the feedstock, e.g. in case of unsustainable deforestation. Tropical deforestation for agriculture and tree plantations, which together released 2.6 Gt $CO_2$ each year between 2010 and 2014, are the second largest anthropogenic source of greenhouse gases. These emissions are typically not taken into account in consumption-based calculations. It is estimated that 29-39 % of the deforestation-related emissions were caused by international trade and Europe is together with China the major importer of goods. The deforestation emissions are calculated to be a substantial share, 15 %, of to the total carbon footprint of food consumption in the EU countries. (Pendrill, et al, 2019)

Carbon losses from soil also need to be taken into consideration – globally soil stores carbon for the long term as much as the biomass itself: 1 550 Gt C in soil compared to 760 Gt C in atmosphere. Current agricultural practices cause losses in the soil storages, in UK between 1978 and 2003, for example, 13 % of carbon stock has been lost from the soil. (Hermann, et al., 2011)

According to a recent study from the Confederation of European Paper Industries (2020), the total climate effects of the forest-based sector in EU27+3 ([13]) in 2018 was -806 Mt $CO_2$eq per year, approximately 20 % of EU's fossil emissions.

The benefit of biobased plastics lies in their sustainable sourcing; the greenhouse gas emissions of the value chain are impacted mostly by the type of raw material that is been used.

**Refining and polymer production and conversion**

For biomass, there are several ways for refining and processing the raw material further and in many cases, the biobased monomers can be produced via several routes. Typically the raw material is refined further (e.g. to acids, glycerol or glucose) to precursors for the monomer production phase, which are further polymerized. The main three production approaches are:

- use of natural polymers, such as starch-based plastics
- polymerisation of bio-based monomers and oligomers through fermentation or conventional chemical processes, such as polylactic acid;
- polymerisation through bacterial fermentation, for example, polyhydroxy alkanoates.

There was a significant variation in the review results of the GWP of bio-based polymers; within single biopolymers, the range can even vary by as much as 9.50 kg $CO_2$-eq/kg of material (see 2.3.3). Between polymers, the fluctuations are also large, but somewhat aligned with the variations of between fossil-based polymers.

Currently, 26 % of the global bio-based production capacity is located in Europe. The prediction to 2024 is that the production capacity will increase to 31 % in Europe.

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[13] EU 27 + Norway, Switzerland and Turkey

If all the fossil-based plastics produced in 2015 had used biomass as its feedstock, the demand for would have equalled 5 % of the total amount of globally produced and harvested biomass. Using current plastics production technologies, however, the current demand could not be met from bio-based feedstock.

**Use phase**

Bio-based plastics can be divided into three categories:
- biobased and biodegradable (for example, bio-polyethylene and bio-polypropylene);
- bio-based and non-biodegradable (for example, polyhydroxy alkanoates and starch blends);
- Fossil-based and biodegradable (for example, polybutyrate adipate terephthalate).

Currently 45 % of bioplastics on the market are not biodegradable while 55 % are.

Even though bio-based plastics can offer an alternative to fossil-based ones, the environmental impact is important to evaluate on a case-by-case basis. In many cases the bio-based plastics can act as an alternative, but, for example, more material might have to be used to compensate for lower properties.

**End-of-life – waste management**

The plastics value chain has untapped potential to reduce $CO_2$ emissions due to low recycling rates; the benefit of closed-loop/high value/qualitative recycling both avoids incineration and primary production.

The mechanical recycling of biobased plastics has a positive effect on the greenhouse gas balance. The effects on the secondary and subsequent lifecycles are also positive as these lower demand for virgin raw materials.

Greenhouse gas emissions from the incineration of biobased plastics are similar to those from fossil-based plastics, the difference lies in the incinerated carbon being either fossil or renewable carbon. Renewable carbon calculations might take into account that incineration of renewable carbon is carbon neutral.

Composting results in $CO_2$, methane and nitrous oxide emissions. Based on one study case, the greenhouse gas emissions from biodegradable polymers was on average 1.62 kg $CO_2$-eq/kg of material. (Jakobsen 2020) This is high when compared to recycling, incineration and landfilling emissions reviewed and used in this report.

Composting is sometimes also accounted for as carbon neutral due to sequestering during feedstock production. Existing research suggests that at least half of the compostable plastics is transformed into $CO_2$ emissions in composting during biodegradation. For composting, the evidence is sparse and inconclusive whether the composting of plastics results in ecological improvements, and also there seems to be a consensus plastic composting resulting in a lack of nutritional benefits. (Jakobsen 2020)

## 3.1. Introduction

The finite nature of fossil-fuel resources and their link to environmental issues, especially climate change, have boosted the uptake of bioeconomy initiatives in which bio-based plastics are used to replace fossil-based plastics. Bio-based plastics are promising alternatives that have the potential to reduce dependency on finite fossil-fuel resources and could also mitigate climate change by reducing greenhouse gas emissions compared to their fossil-based alternatives. It needs to be noted, however, that the production of raw materials for biobased plastics require the use of land in competition with food production. As a result, the demand for bio-based and biodegradable plastics is increasing although currently they only make up around 1 % of global plastic production. (European Bioplastics, 2018). The EC's Strategy for Plastics in a CE highlights biobased feedstocks as alternative ones to avoid using fossil resources and help transition the plastics economy from a linear to a circular model.

According to European Bioplastics, several lifecycle analyses show significant $CO_2$ savings for biobased plastics compared to conventional fossil-based ones. A lifecycle analysis is, however, always dependent on a variety of factors, such as feedstock, product, application and end-of-life treatment. The important lifecycle stages linked to the climate change impacts are the production and processing of biomass, but in many lifecycle analyses, the lifecycle stages were not characterised separately. The analyses suggest that the use of biobased plastics would help the EU meet its greenhouse gas reduction targets, especially when the carbon-neutral or carbon-sink potential of biobased plastics, which links to the amount of biobased carbon contained in material or product, is included (EUBP, 2019) However, the risks related to the potential direct and indirect land-use changes due to the growing demand for biobased plastics need to be properly evaluated as well – the way that these effects are factored in are currently discussed for biofuels but not biomaterials, and are not standardised. Issues such as deforestation and changes in land $CO_2$ sequestration can further contribute to climate change by decreasing sequestration capacity and/or further increasing greenhouse gas emissions.

It should to be noted that both bio- and fossil-based plastic contain carbon that can be released completely as $CO_2$ when incinerated and that the production of both cause $CO_2$ emissions. The advantage of biobased plastics is that they take up atmospheric carbon through the feedstock phase (sequestration), that can be accounted for as a negative greenhouse gas emission flow, but this is neutralised when it is incinerated, releasing $CO_2$. Due to a lack of standardisation, in some lifecycle analyses biomass is considered to be carbon neutral with the actual $CO_2$ uptake and release not taken into consideration. CE Delft (2017) defines two main ways of calculating the related greenhouse gas emissions related to biobased carbon when the biomass is assumed to be sustainably grown;

1) The biomass $CO_2$ uptake is included as negative emissions and at the end-of-life stage emitted as positive greenhouse gas emissions,
2) the biomass $CO_2$ uptake and end-of-life stage emissions are both zero.

The negative GHG emissions can for example relate to sequestered (non-released) carbon that is included as non-emitted or stored carbon, or for example include co-products credits. The challenge in comparing fossil- and bio-based plastics is that there are many different plastic products and demands for different properties, as well as a lack of data. Data are available from case studies on specific products and polymers, but data from comprehensive analyses are limited. Hoffman et al. (2019) stated that the calculation of the environmental burdens of end-of-life plastics has been neglected in many studies due to the difficulty in quantifying them using conventional lifecycle assessments. This report’s analysis of greenhouse gases and bio-based plastics analysis was carried out through a review of relevant studies. The review of greenhouse gas emissions from biobased plastics and conventional plastics used the same value chain perspective, including feedstock production, refining and processing, production (conversion), use, waste management and leakage of plastic waste to the environment.

The benefit of biobased plastics lies in sustainable sourcing as the emissions of the value chain are impacted mostly by the type of raw material used. The resource sufficiency is dependent on whether the material is recirculated. Currently, the hindering factor for bio-based plastics’ potential to mitigate climate change and enhance material sufficiency is the reality of the lack of recycling of biobased plastics. (EEA 2020a). Even though biobased plastics could fit into a circular economy through different reuse and recycling options, the low waste volumes available and, to some extent, the non-compatibility with the recycling of fossil-based plastics are limiting their circularity potential. Non-biodegradable bio-based plastics typically end up in incineration, whereas composting is an option for material recovery for biodegradable ones (Tenhunen, et al., 2020; EUBP, 2019)

To study the overall potential and challenges around bio-based plastics, available studies were reviewed to provide a range of overall greenhouse gas emissions or GWP figures. Spearling et al. (2018) reviewed 29 lifecycle analyses of bio–based plastics in which biogenic carbon was included. In all of these studies, GWP was in the range of -0.3–11.9 kg $CO_2$-eq/kg for bio-based plastics. Plastics Europe has reported a GWP range from 1.6– 6.4 kg $CO_2$-eq/kg for conventional fossil-based plastics. The study estimated a substitution potential of 65.8 % of all fossil-based plastics on a global scale. Spierling et al (2018) study shows the impacts related to GWP of the global plastics demand caused by fossil- and bio-based plastics respectively (Spierling et al., 2018). The results indicate that the impact varies between polymers and that within some solutions, especially bio- polyethylene, there is a wide discrepancy between minimum and maximum values. The Spierling et al. study focused on only the two thirds of plastics production in which substitution was technically possible.

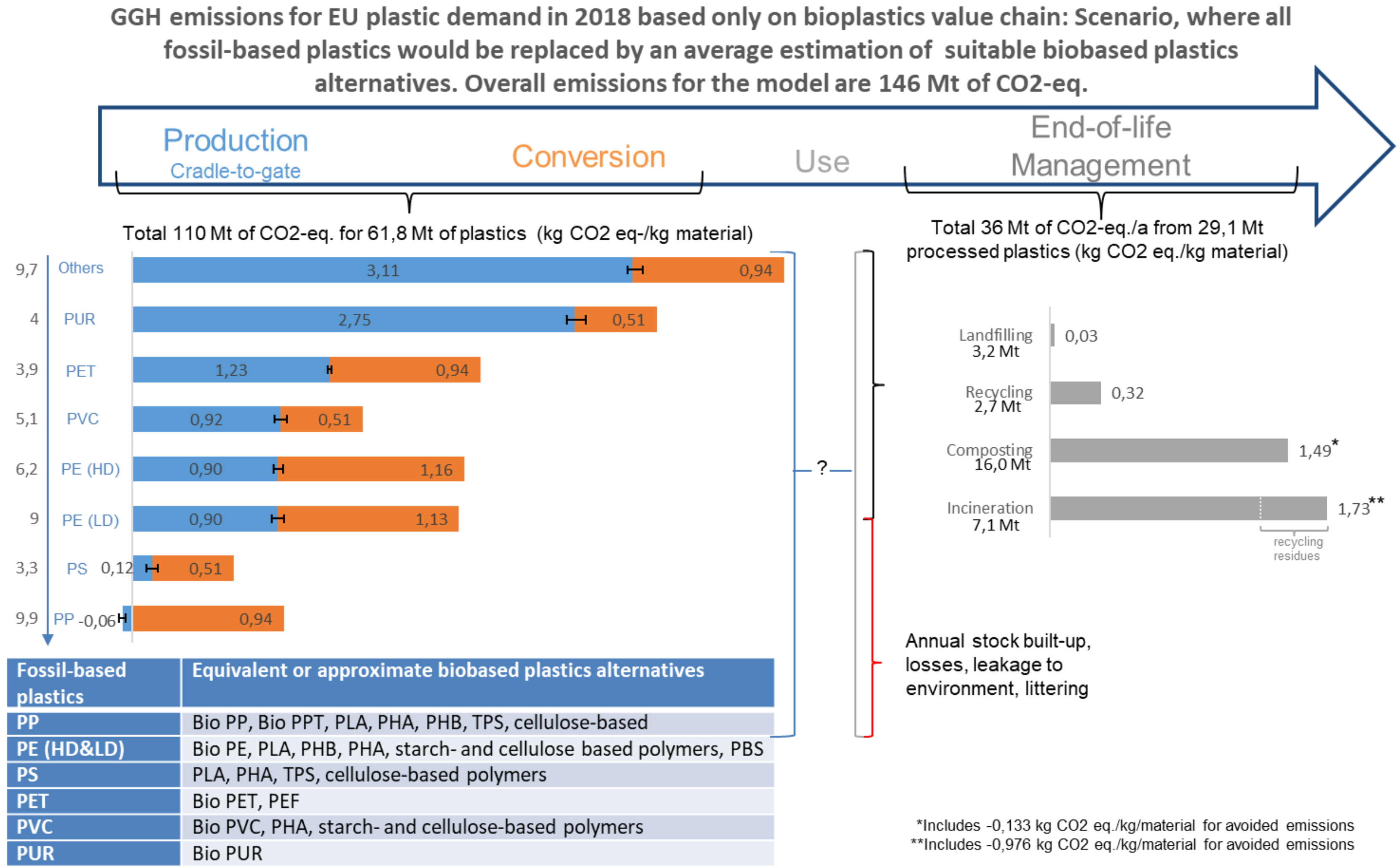
In the review of the overall sustainability of bio-based plastics, Spierling et al. (2018) calculated that bio-based plastics could, on an annual basis, potentially save 241–316 Mt of $CO_2$-eq if they replace approximately two thirds of the global demand for plastic. These calculations consider the technical substitution potential of fossil- with bio-based plastics as well as the limitations in data availability. The potential focused on both non-biodegradable (bio-polyethylene, bio polyamides and bio-polyurethane) and biodegradable (polylactic acid, starch blends and polyhydroxy alkanoates) plastics (Spierling et al., 2018). The study focused on environmental impacts of global warming potential. Spierling et al. also highlighted that, due to assessment challenges, the land-use impact category is hardly used in lifecycle analyses, although it is crucial for environmental impact assessments of biobased plastics.

The current overall emissions from biobased plastics are very low compared to those from fossil-based ones due to the fact that their market share is very small. In 2019, more than 3,8 Mt of bio-based plastics were produced globally (European Bioplastics 2019). Even though it has been acknowledged that the existing bio-based plastics production technologies could not meet the current total demand for plastics and that there are also challenges in biobased plastics attaining equivalent properties to high performing fossil-based ones, an attempt to estimate the overall greenhouse gas emissions from biobased plastics if all the plastics used in the EU today were replaced with bio-based alternatives has been made in this study. As far as land use for this scenario is concerned, based on the calculations of Oever et al. (2017) and the volume of EU plastic consumption, approximately 0.8 % of global arable land would be required to meet the demand for plastics with biobased plastic.

A big uncertainty in this estimate lies in the fact that the range of greenhouse gas emissions for biobased plastic value chains were collected from different case studies that are challenging to compare due to differences in the methodologies used and that the polymer-based averages used may have rather high deviance. Furthermore, the generalisation of fossil- versus bio-based replaceability does not fully represent reality. The complexity of bio-based value chains needs to be taken into consideration when evaluating the simplified estimation. An average of fossil-based plastics' greenhouse gas emissions from conversion, recycling, incineration and landfilling has been used for bio-based plastics calculations as well. The use phase has not been taken into consideration as the greenhouse gas emissions are hard to connect to the polymeric materials, such as plastic components in a fuel-based car that is used for transport. Currently, about 55 % of biobased plastics on the market are biodegradable, thus, an estimate was made that 45 % of the bio-based plastics would go through the same processes as conventional plastics today – recycling, incineration, and landfilling – and that the remaining 55 % would be composted. The scenario estimation for composting is done on the current situation of what would be possible to compost, this does not reflect on the future trends of end-of-life-management of biobased plastics.

To sum up, the methodology for the scenario has been built based on the following steps: 1) a biobased-polymer average for GHG emissions for cradle to gate has been calculated based on a literature review and case studies (Figure 3-4), 2) a literature review has been made to match the fossil plastics with biobased plastic alternatives, 3) the European polymer-based production volumes have been matched with the bio-based alternatives, 4) the end-of-life management part is based on the current situation that 55 % is compostable and 45 % is not. The 45 % that is not composted is divided into landfilling, incineration and recycling as the fossil-based plastics flow today. The end-of-life-management GHG emissions related to each step was gathered so that landfilling, incineration and recycling have the same factor as the fossil-based section of this report and the composting was reviewed from literature. Based on these conditions, an estimate for the overall greenhouse emissions from the EU's plastic demand based on bio-based plastics is approximately 146 Mt of $CO_2$-eq in total, which is 62 Mt or 30 % less than the emissions for the fossil-based value chain calculations of 208 Mt (see Figure 3-1).

*Figure 3-1 Scenario calculations for EU plastic demand solely based on bio-based value chains*



| Fossil-based plastics | Equivalent or approximate biobased plastics alternatives |
|---|---|
| PP | Bio PP, Bio PPT, PLA, PHA, PHB, TPS, cellulose-based |
| PE (HD&LD) | Bio PE, PLA, PHB, PHA, starch- and cellulose based polymers, PBS |
| PS | PLA, PHA, TPS, cellulose-based polymers |
| PET | Bio PET, PEF |
| PVC | Bio PVC, PHA, starch- and cellulose-based polymers |
| PUR | Bio PUR |

**Source**: Calculated based on data used for the fossil-based plastic calculations in this study as well as values collected from a study review of the following studies: Blanco et al. (2020), Brizga et al. (2020), Dilkes-Hoffman et al. (2019), Pendrill et al. (2019), Spierling et al. (2018), CE Delft (2017), Vink and Davies (2015), (Shen et al. (2012) and Kim and Dale (2008).

## 3.2. Release of greenhouse gas emission along the biobased plastics value chain

**Biobased plastics, their share on the markets and potential**

Biobased plastics are mostly made from agri-based and lingocellulosic feedstock. Some waste materials from, for example, agriculture are also used or are projected to be used in growing amounts. Sustainable sourcing of biomass is addressed by several sustainability certification schemes (EUBP, 2019). Biobased plastics can be primarily categorised by the origin of feedstock (biological materials), and then divided into biodegradable and compostable plastics as well as those plastics that degrade into fragments through physical or chemical processes (EEA 2020a).

The global production capacity for bio-based polymers is increasing steadily; Chinthapalli et al. (2019) estimate that the annual growth rate to 2024 is about 3 % by when total capacity will be 4.9 Mt. This is similar to the estimated growth rate for fossil-based polymers. The bio-based polymer sector is very versatile: several different feedstocks are used to produce a wide range of different polymers through different intermediates and building blocks. The 2019 3.8 Mt production consists of structural polymers where the main polymers are epoxy resin, polyamide ,polyethylene, polyethylene teraphtalate and polylactic acid (Chinthapalli et al. 2019).

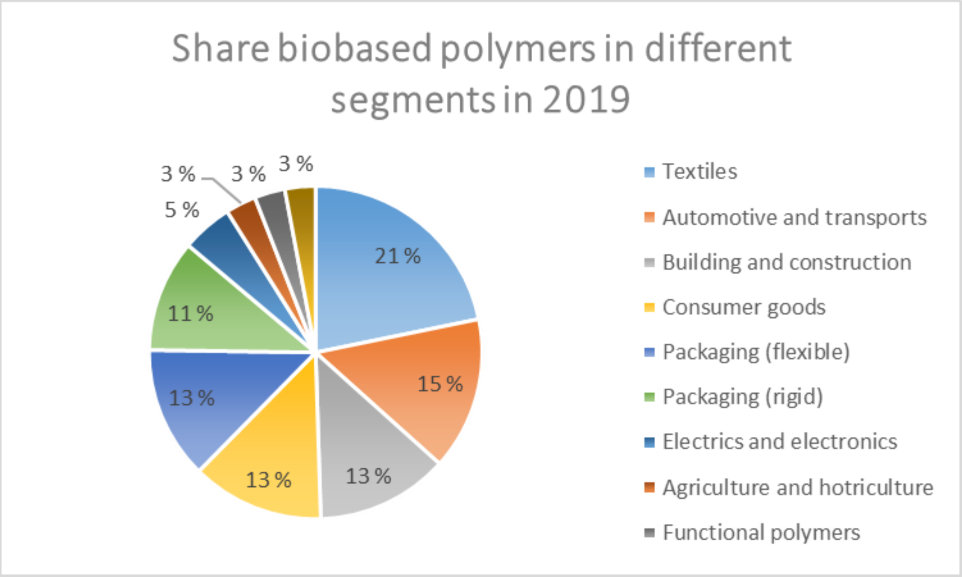
EEA 2020a has divided the bioplastics into three categories:

1) bio-based and biodegradable (for example, bio-polyethylene, bio-polypropylene);
2) bio-based and non-biodegradable (for example, polyhydroxy alkanoates, starch blends);
3) fossil-based and biodegradable (for example, polybutylene adipate-co- terephthalate).

In 2019, about 55 % were biodegradable while the remaining 45 % were not. The majority of biodegradable plastics are used in flexible and rigid packaging, in agriculture and horticulture, as coatings and adhesives, and in other consumer goods (EUBP, 2019), Currently, 26 % of the global bio-based production capacity is in Europe, and this is predicted to increase to 31 % by 2024 (Chinthapalli et al. 2019).

The different bio-based plastics have a range of different functionalities that can be used in different applications (EUBP, 2019). The main applications are in short-term products in packaging, 24 % including both rigid and flexible packaging; textiles, 22 %; automotive, 15 %; building and construction, 13 %; consumer goods, 13 % (Chinthapalli et al. 2019) (Figure 3-2). Bio-based plastics are typically processable into products using the same machinery as fossil-based ones with only small processing adjustments, known as drop-ins (European Bioplastics 2019).

*Figure 3-2 Share of bio-based polymers in different market segments, 2019, per cent*



**Source**: Redrawn from Chinthapalli et al. (2019)

Oever et al. (2017) estimated that had all fossil-based plastics in 2015 been produced from biomass, the demand for feedstock would have amounted to 5 % of all biomass produced and harvested globally. It has, however, also been calculated that existing bio-based plastic production technology could not meet current demand. There are also challenges in ensuring bio-based plastics and high-performing fossil-based plastics have equivalent properties. Some biobased plastics and their fossil-based equivalents are shown in Table 3-1.

*Table 3-1 Bio-based alternatives to some of the most widely used fossil-based plastics*

| Fossil-based plastics | Equivalent or approximate biobased plastics alternatives |
|---|---|
| PP | Bio-PP, Bio-PPT, PLA, PHA, PHB, TPS, cellulose-based |
| PE (HD and LD) | Bio-PE, PLA, PHB, PHA, starch- and cellulose-based polymers, PBS |
| PS | PLA, PHA, TPS, cellulose-based polymers |
| PET | Bio-PET, PEF |
| PVC | Bio-PVC, PHA, starch- and cellulose-based polymers |
| PUR | Bio-PUR |

**Source**: Blanco et al.(2020), Brizga et al. (2020), EASAC (2020), Dilkes-Hoffman et al. (2019), Morão and de Bie (2019), Lewandowski (2018) and Spierling et al. (2018)

To approximately quantify the greenhouse gas emissions from the existing and potential biobased plastics value chains, the different stages were reviewed separately. The emissions from the conventional plastics' value chain have been applied to those parts of the bio-based value chain that are similar –conversion, mechanical recycling, incineration, and landfilling.

### *3.2.1 Feedstock production*

Bio-based plastics are made from renewably sourced raw materials, mainly carbohydrate rich agri-based sources, such as corn or starch, and non-edible lignocellulosic feedstock from, for example, wood-based sources. Organic waste and side streams are also used as feedstocks and algae-based solutions are currently being investigated. It should be noted that typically there are cascading uses for different biomass fractions and side streams. As plants grow, they absorb atmospheric $CO_2$, sequester the carbon and release oxygen. As long as the bio-based material is in use, the carbon is stored within it. Emissions from land use include emissions from the net conversion of forests, cropland and grassland and the burning of biomass for agricultural and other uses. Carbon losses from soil also need to be considered – twice as much carbon is stored in the soil as in the atmosphere: 1 550 Gt C in soil versus 760 Gt C in the atmosphere. Agricultural practices can cause losses from the soil – in United Kingdom between 1978 and 2003, 13 % of the soil carbon stock was lost (Hermann, et al., 2011).

Agricultural emissions related to feedstock production originate from manure use and management, synthetic fertilisers, crop residues and their incineration. Furthermore, transport related emissions are typically high. If renewable biomass is used as a feedstock account should be taken of the $CO_2$ removes from the atmosphere. Thus, if renewable biomass is used, there is an additional benefit beyond the avoided extraction of those fossil resources. The benefit of biobased plastics lies in sustainable sourcing of feedstock as the the value chain's greenhouse gas emissions are mostly impacted by the type of raw material used. The biggest variations in different lifecycle analyses resulted from the use of different raw materials. However, the effects of land use are not typically included in such studies due to the challenges of assessing them. The direct- and indirect impacts of land use can affect the overall emissions of biobased plastics. In a report on the circular economy, (CE Delft 2017) assessed the indirect effect of land use change was rather small for raw materials derived from wheat, maize, sugar beet and sugar cane – a maximum of 10 % of emissions, while that from oil crops is significantly higher.

Forests are very important carbon sinks. Negative impacts can relate to the unsustainable sourcing of the feedstock from deforestation, which can also relate to bioplastics e.g. through wood-based biobased plastics or through conversion of tropical forests for raw material production for biobased plastics. Pendrill et al. (2019) suggest that the conversion of tropical forests for agriculture and tree plantations is the second largest source of anthropogenic greenhouse gases, releasing 2.6 Gt $CO_2$ annually between 2010 and 2014. Of the tropical deforestation-related emissions 29–39 % were caused by the international timber trade – Europe together with China are the major importers of wood and wood products. The emissions resulting from were shown to contribute a substantial share, 15 % of to the total carbon footprint of food consumption in the EU countries. The emissions from deforestation are not typically taken into account in consumption-based calculations. There is a lack of data; the existing studies on emissions from deforestation are outdated or only cover some areas or countries (Pendrill et al. 2019) According to a recent study from the Confederation of European Paper Industries (CEPI) (2020), the total climate effects of the forest-based sector in EU27+3 countries was -806 Mt $CO_2$eq/year in 2018, which is approximately 20 % of EU's fossil-based emissions. This takes into consideration the following factors; 1) net forest sink, 2) harvested wood products (HWP) sink, 3) fossil-based emissions used for the forest value chain, 4) substitution, and 5) traditional energy sources (CEPI 2020).

Table 3-2 provides some examples of primary or feedstock production-related data on $CO_2$ emissions. It should be noted that these only contain the anthropogenic emissions and exclude the natural carbon cycle releases such as $CO_2$ from organic matter to soil. Some studies containing primary or feedstock production data are available, but the link to bio-based plastics, calculations of $CO_2$-eq emissions per produced polymer, is missing in many cases. Typically, the emissions for different bio-based raw materials are calculated as kilograms per area while fractions of the harvest are used for a variety of different applications. Then again, for different technologies and different quality feedstock, input quantity requirements vary. This shows the complexity of bio-based value chains and the challenges in calculating their overall emissions.

*Table 3-2 Examples of greenhouse gas emissions from primary production.*

| **Feedstock** | **Greenhouse gas emissions** | **Notes** |
|---|---|---|
| Grain output | 0.15 kg $CO_2$-eq/kg PHA | including seed, fertilisers, chemicals, excluding stover. |
| Glucose | 1.510 kg $CO_2$-eq/kg PHA | including fertilisers, process water, electricity, steam, cooling water, based on renewable energy. |
| Soybean oil | -0.040 $CO_2$-eq kg/kg PHA | including fertilizers, process water, electricity, steam, cooling water, based on renewable energy. A negative GHG emissions value can be due to inclusion of co-products credits or assumption -1 for the carbon uptake. |

**Source**: Yu and Chen (2008)

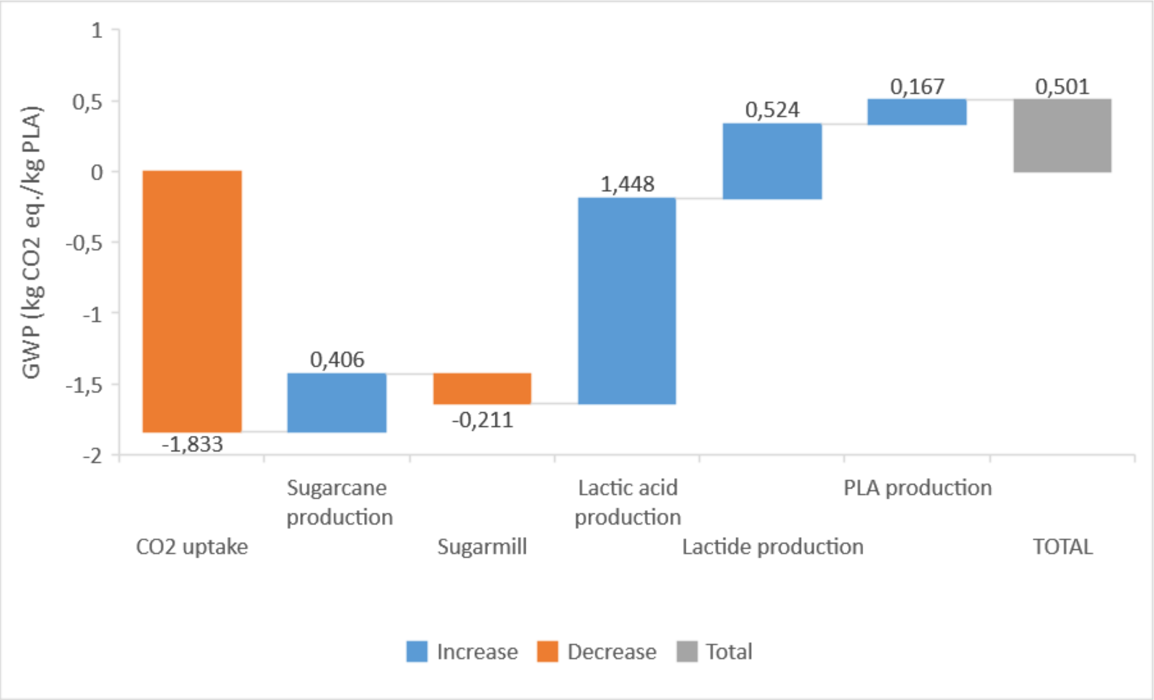
### 3.2.2 Refining, polymer production and conversion

There are several ways of refining and processing biomass and in many cases, bio-based monomers can be produced in several ways. Typically, the raw material is refined into precursors, such as acids, glycerol or glucose, for the monomer production phase. These monomers are then polymerised and finally converted into plastic products. The main three approaches are:

1) the use of natural polymers, such as in starch-based plastics;
2) the polymerisation of bio-based monomers and oligomers through fermentation or conventional chemical processes, for example, for the production of polylactic acid;
3) the polymerisation through bacterial fermentation, used, for example, in the production of polyhydroxy alkanoates.

Figure 3-3 provides an example of the process of biopolymer production and calculations relating to the GWP of polymers. Polylactic acid production's lower total GWP is heavily dependent on the $CO_2$ uptake during the growth of sugarcane. The most intense part of the value chain is the lactic acid production phase. Additionally, Figure 3-4 shows the GWP considerable variance in the production phase of different bio-based polymers. It is also important to note, that sometimes the biopolymers are only partly based on biological raw materials.

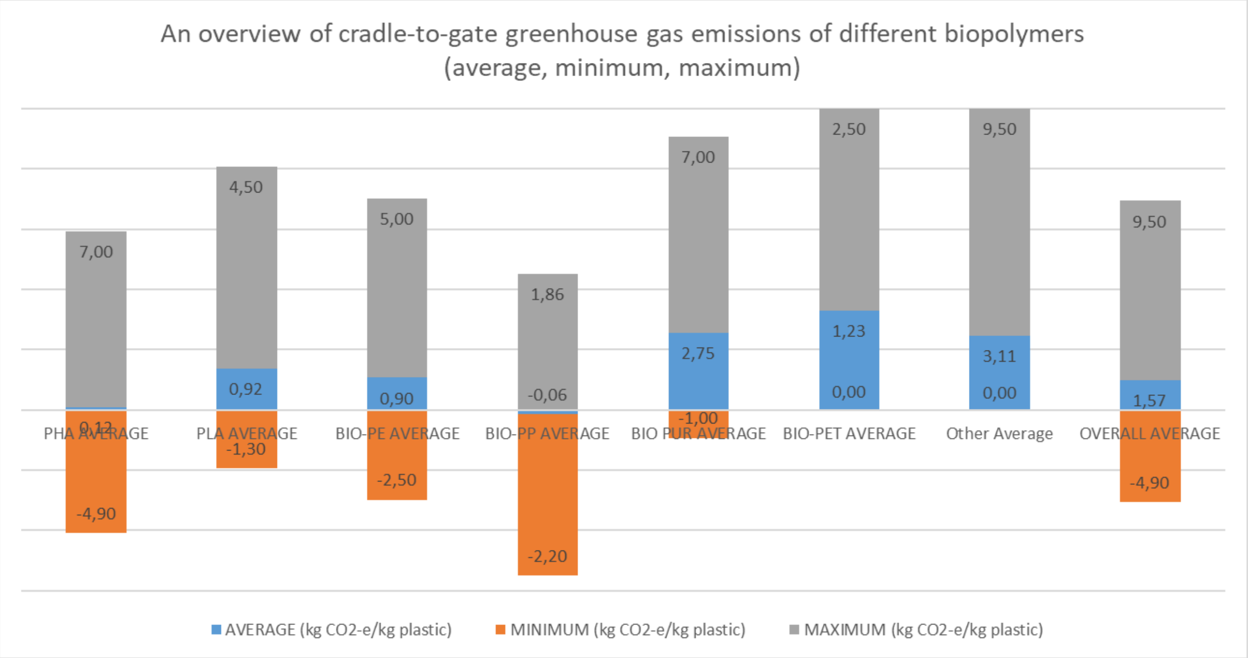
*Figure 3-3* *Contribution of different production stages to the total global warming potential of polylactic acid from the $CO_2$ uptake during growth to production plastic pellets, kg $CO_2$-eq/kg polylactic acid*



**Source**: Morão and de Bie (2019), redrawn

A literature-based review of cradle-to-gate analyses of different biopolymers is presented in Figure 3-4. Cradle-to-gate covers the raw material acquisition and pre-processing – the extraction of natural resources and the steps up to the components entering to the product production facility. The results vary considerably depending on the methodology used for calculations, whether they originate from specific case studies or were generalised/rounded for other purposes such as a general overview.

*Figure 3-4 Greenhouse gas emissions and their ranges for different biopolymers from cradle to gate based on case studies*



**Source**: (Blanco, Ingrao, and Siracusa 2020), (Brizga, Hubacek, and Feng 2020), (Dilkes-Hoffman et al. 2019), (Pendrill et al. 2019), (Spierling et al. 2018), (CE Delft 2017), (Vink and Davies 2015), (L. Shen, Worrell, and Patel 2012) and (Kim and Dale 2008).

### Bio-ethylene production

Bio-ethylene production is based on bio-ethanol. Fermentation of sugars in the biomass occurs in when it is distilled to make bio-ethanol, which are then dehydrogenated to produce ethylene. Biomass can also be gasified into syngas, then converted into methanol and then olefins, but this is not an advantageous process in terms of $CO_2$ emissions (Bazzanella 2017).

It is estimated that the bio-ethanol production step prior to ethylene synthesis produces around 1 tonne $CO_2$-eq/tonne ethylene. The biogenic carbon sequestered in the product, which is stoichiometrically counted as negative emissions amounts to 3.14 tonne $CO_2$-eq/tonne ethylene. A case by case analysis of the carbon footprint is strongly advised for bio-ethylene production, as the carbon footprint depends on the type of biomass used, the local production logistics and infrastructure (Bazzanella 2017).

### Biopropylene production

Biopropylene can be produced through biomass gasification, methanol synthesis and methanol to olefins (MTO)/methanol to propylene (MTP). The synthesis route through gasification to methanol requires 2.6 tonnes of dry biomass per tonne of methanol and the MTO route stoichiometrically requires 2.28 tonnes of methanol per tonne of propylene. Total biomass demand is therefore at least 5.9 tonnes per tonne of propylene. Process related $CO_2$ emissions are at 1.86 tonne $CO_2$-eq per tonne of propylene, which is a 2.5 times those of the fossil-based route using naphtha steam cracking. Sequestered bio-based carbon amounts to 2.09 tonne $CO_2$-eq/tonne of propylene, which slightly overcompensates the process emissions, however, the gain is low (Bazzanella 2017).

### Butene toluene xylene production from biomass

The production of butene toluene xylene (BTX) from biomass can follow several routes. The most developed is gasification of biomass, followed by methanol synthesis and conversion of methanol to aromatics (MTA). Fast pyrolysis of lignocellulosic biomass would be another option though the technology is, as yet, less developed. Depending on the process, $CO_2$ emissions are between 2.21 and 2.6 tonnes $CO_2$-eq/tonne of butene toluene xylene. This is two to three times higher than of the fossil-based route, 0.84 tonnes $CO_2$-eq/tonne of butene toluene xylene (Bazzanella 2017). Overall emission reductions would therefore originate only from the bio-based carbon sequestered in the products, which amounts to 3.3 tonnes $CO_2$-eq/tonne of butene toluene xylene, resulting in a total carbon footprint of -0.7 to -1.54 tonnes $CO_2$-eq/tonne of butene toluene xylene avoided $CO_2$ compared to the fossil-based route.

*Table 3-3 Comparison of biomass-based synthesis routes*

| Product | Biomass as feed for production of 1 tonne (tonnes) | Δprocess $CO_2$ emissions compared to fossil route (tonnes) | Biogenic carbon sequestered as $CO_2$ (tonnes) | Avoided $CO_2$ per tonne biomass (tonnes) |
|---|---|---|---|---|
| Biomethanol | 2.6 | -0.2 | -1.37 | 0.600 |
| Bioethylene | 10.5 | +0.05 | -3.1 | 0.290 |
| Biopropylene | 5.9 | +1.1 | -2.09 | 0.170 |
| Bio-BTX | 11.2 | +1.76 | -3.3 | 0.139 |

**Source**: Bazzanella (2017)

### Polyhydroxy alkanoates fermentation

Fermentation is used for example for polyhydroxy alkanoates production. Some examples of greenhouse gas emissions from its production from different feedstocks are shown in Table 3-4.

*Table 3-4 Examples of greenhouse gas emissions from biobased plastics processing steps*

| Processing step | Greenhouse gas emissions | Notes |
|---|---|---|
| Fermentation (of PHA) | maize: 1.73 $CO_2$-eq kg/kg PHA<br>glucose: 1.510 $CO_2$-eq kg/kg PHA<br>Soybean oil: -0.040 $CO_2$-eq kg/kg PHA | Maize: Including inoculum preparation, fermentation, product recovery and auxiliary operation and maintenance. Total fossil energy 26.52 MJ/kg PHA. Wastewater treatment total of 0.27 kg CO2-eq/kg PHA<br>Glucose and soybean oil: including fertilisers, process water, electricity, steam, cooling water, based on renewable energy. |

**Source**: Yu and Chen (2008)

### Conversion

The conversion of bio-based plastics to products, especially drop-ins, is similar to fossil-based plastics. Their processability is not very different from fossil-based processing, but because the various bio-plastics have different properties from their fossil counterparts, their thermal processing may differ, for example the moulding temperature can be lower or higher. In some cases, special processing techniques may be needed that might alter, for example, energy requirements (Feldmann and Fuchs, 2016). For the bio-based value chain greenhouse gas calculations, the same assumptions were used as for the fossil-based value chain (section 2.2.3).

### 3.2.3 Use phase

Only 1 % of all plastics are bio-based, but a wide range of different biopolymers is available. Even though bio-based plastics can offer an alternative to fossil-based ones, it is important to evaluate the environmental impacts case by case. In many cases the bio-based plastics can act as an alternative, but more material might have to be used to compensate for lower properties. For instance, in assessing lifecycle greenhouse gas emissions, Nova Institute (2017) calculated emission reductions of around 27 % relative to fossil fuels in producing polylactic acid, while Shen et al. (2012) calculated that producing polyethylene teraphtalate bottles from biobased plastic emits, on average, 25 % fewer greenhouse gases relative to petroleum. Comparing fossil- and bio-based polyethylene teraphtalate bottles, Yu and Chen (2008) suggested using woody biomass would deliver a potential reduction in GWP of 21% relative to fossil fuels. Furthermore, on a global level it has been estimated by EASAC (2020) that to replace polyethylene, polyethylene teraphtalate or polypropylene with the biopolymers polybutylene succinate or polylactic acid would require 15.9–19.5 % of current global wheat production and replacing polyethylene by a bio-polyethylene would require 93.5 % of global wheat production (EASAC 2020).

Below present example two case are presented in which the same fossil polymer was substituted with polylactic acid and polyethylene furanoate.

**Case example 1: Bottles – polyethylene teraphtalate compared to polylactic acid**

A study was conducted to compare bio-based polylactic acid with fossil-based polyethylene teraphtalate in bottles. Polylactic acid has lower barrier properties, which limits its shelf life as bottles and makes it unsuitable for with carbonated drinks. As the performance is different, more material is needed for a polylactic acid-based drinking bottles than for polyethylene teraphtalate ones – 22–25 grams of polylactic acid against 10–20 grams of polyethylene teraphtalate. For the study, different weight scenarios were formed. For same weight bottles, those made of polylactic acid had lower greenhouse gas emissions than polyethylene teraphtalate bottles, but if the polylactic acid bottles were twice the weight of the polyethylene teraphtalate ones, then the emissions would be similar to both types of bottle (Shen et al. 2012)

**Case example 2: Bottles – polyethylene teraphtalate comapared to polyethylene furanoate**

A promising alternative to fossil-based polyethylene teraphtalate is bio-based polyethylene furanoate as it can have better barrier properties but it is still in the early stages of large-scale production. Eerhart et al. (2012) compared the greenhouse gas emissions of polyethylene furanoate and polyethylene teraphtalate, finding in cradle-to-grave analysis that the substitution of polyethylene teraphtalate could reduce emissions 45–55 % . The reductions are much higher with polyethylene furanoate than with, for example, polylactic acid. A study by Jiang et al. (2020) found that emissions and energy consumption could be reduced by up to 40.5 % when polyethylene furanoate is compared to polyethylene teraphtalate.

### 3.2.4 End of life - waste management

Technically, the end-of-life treatment options for biobased plastics are in many cases the same as for conventional fossil-based ones. Additionally, biodegradable biobased plastics can be composted while non-biodegradable bio-based plastics are typically incinerated. If incineration is coupled to electricity generation, there can be some sustainability gains. Recycling is a preferred option, keeping the material in circulation, but for bio-based plastics it is not currently a prevailing route due to different bottlenecks and barriers including separation challenges, insufficient collection schemes and a lack of collection volumes for mechanical recycling. The energy intensity of end-of-life options is highly dependent on the technology, but generally speaking the end-of-life options are somewhat energy intensive and a big part of the overall sustainability of end-of-life treatment is dependent on the source of energy. Nonetheless, recycling materials results in decreased need for virgin raw materials, which produces savings from the virgin plastic production phase. It is hoped that (thermo) chemical recycling will bring further possibilities of increasing the recycling of bio-based plastics.

End-of-life options, incineration, mechanical recycling, industrial composting, landfilling and leakage to environment, were reviewed for biobased plastics. Anaerobic digestions and production of biogas was not separately studied in this review. In some places, such as the Netherlands, anaerobic digestion is used after composting. It should to be noted, however, that not many bio-based polymers are well digested in anaerobic conditions (Hermann et al., 2011).

### Incineration

Since biomass is a feedstock for bioenergy production, a lot of data can be found on greenhouse gas emission relating to its incineration. Studies typically include the cradle-to-fuel lifetime – cultivation, harvesting, processing and transportation to warehouses and power plants – as well as the combustion. Studies on greenhouse gas emissions from plastic incineration, however, are scarce. It is also important to distinguish whether the incineration is coupled to energy recovery. Typically, incineration with energy recovery results in energy production that is considered carbon neutral. A study by Hermann et al. (2011) calculated the net GWP of incineration of some biodegradable polymers (Table 3-5). The incineration of bio-based plastics has similar emissions to fossil-based plastics: 2.71 kg $CO_2$-eq./kg of material was used in this study for the calculation of fossil-based and biobased plastics incineration for direct and indirect emissions, and -0,976 kg $CO_2$-eq./kg for avoided emissions because of energy recuperation

*Table 3-5 Biodegradable polymers' incineration related GWP results*

| | **Material** | **Net GWP (kg $CO_2$-eq/kg of material)** |
|---|---|---|
| **Biodegradable polymers** | PLA | 1.24 (1.83) |
| | Stratch/PCL | 1.26 (1.99) |
| | Starch | 1.08 (1.63) |
| | PHBV | 1.31 (2.12) |
| | PBAT | 1.36 (2.29) |
| | Average | 1.25 (1.97) |

**Notes:** numbers expressed: with energy recovery (without energy recovery)
**Source**: Hermann et al. (2011)

### Mechanical recycling

Mechanical recycling includes the following process steps: collection, sorting, washing and grinding. Even though bio-based plastics can be recycled – they are recyclable and many through existing infrastructure – they do not get recycled. This is due to the economic feasibility of recycling low volumes, challenges in collection schemes and insufficient separation. With regard to compostable plastics in conventional mechanical plastics recycling, reports indicate that the final levels of contamination are acceptable to subsequent recycling processes. However, this refers to a scenario in which compostable plastics are only used in very small quantities in niche applications. For example, Wageningen Food & Biobased Research looked at food packaging recycling and found out that 200 sorted plastic waste batches, which were collected over five years, contained only 0.01–0.14 % biobased plastics (Oever et al., 2017).

Greenhouse gas emissions from mechanical recycling are similar to those from fossil-based plastics. In 2019 report from Materials Economy, it estimated that mechanical recycling, including the cleaning and upgrading steps, produce 20 % less $CO_2$ emissions than making new plastics even if the energy involved in transport, heating and electricity is neither from clean sources nor carbon neutral (Material Economics, 2019).

### Industrial composting

Composting is a waste treatment option for biodegradable plastics but is also a source for greenhouse gas emissions. Although some studies, including from CE Delft (2017), conclude that composting is $CO_2$ neutral, it depends on the way the calculations are done as, for example, in the case of bioenergy. There is a lack of knowledge about the quality of compost made from compostable plastics but there is direct evidence of ecological improvements being sparse and it lacking of nutritional benefits for soils. Existing research also suggests that at least half of compostable plastic is transformed into $CO_2$ emissions during biodegradation. Contamination with plastic particles is a particular challenge in terms of keeping compost made from separately collected bio-waste clean (EEA 2020a).

The emissions from composting vary depending on the process used as well as process conditions, such as temperature and moisture content. Industrial composting typically takes two to eight weeks for fresh compost and 12 weeks in total including maturing, and is carried out at higher temperatures of around 50–60 °C. The products of biodegradation are $CO_2$, methane, nitrous oxides, solids and water, and industrial composting is dominated by $CO_2$ emissions.

The effects of composting depend on the calculations used for carbon and nitrogen credits. For example, the carbon credit, for example when using compost for soil remediation rather than other soil conditioners, saves carbon from other sources. This is valuable due to the fact that it can counteract carbon and nitrogen losses from agriculture and forestry – the typical GWP of fertiliser production, for example, ranges between 2 and 9 tonnes $CO_2$-eq/tonne of fertiliser. It is also important to note that soil stores carbon, so, in other words, compost stores carbon in the soil. Table 3-6provides some examples of $CO_2$ emissions from composting for certain bio-based materials. The total $CO_2$-eq emissions for biopolymer composting are rather high, on average 1.62 kg $CO_2$-eq/kg of material (for direct and indirect emissions)[14], when compared to recycling, 0.32 kg $CO_2$-eq/kg of material and landfilling, 0.03 kg $CO_2$-eq/kg of material. Only incineration is higher at 2.71 kg $CO_2$-eq/kg of material.

*Table 3-6 Composting related CO2 emissions for selected biobased plastics, 2011, kg CO2-eq/kg of material*

| **Material** | **$CO_2$ (kg $CO_2$-eq/kg of material)** | **Methane (kg $CO_2$-eq/kg of material)** | **Nitrous oxide (kg $CO_2$-eq/kg of material)** | **Total (kg $CO_2$-eq/kg of material)** |
|---|---|---|---|---|
| PLA | 1.47 | 0.018 | 0.10 | 1.588 |
| Starch | 1.30 | 0.016 | 0.09 | 1.406 |
| Starch/PCL | 1.38 | 0.020 | 0.11 | 1.51 |
| PHBV | 1.69 | 0.021 | 0.12 | 1.831 |
| PBAT | 1.60 | 0.023 | 0.13 | 1.753 |
| *Average* | *1.49* | *0.020* | *0.11* | *1.62* |

**Source**: Hermann et al. (2011)

### Landfilling

The methane from landfills and wastewater collectively accounted for about 90 % of the waste sector's emissions and about 18 % of global anthropogenic methane emissions. Although landfill methane emissions in developed countries have been largely stabilised, emissions in developing countries are increasing – these emissions could be reduced were more controlled, anaerobic landfilling practices implemented; by accelerating the introduction of engineered gas recovery, increasing rates of waste minimisation and recycling, and implementing alternative waste management strategies provided they are affordable, effective and sustainable. As landfills produce methane for several decades, incineration and composting are complementary mitigation measures to landfill gas recovery in the short to medium term.

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[14] Avoided emissions for composting are estimated at -0,133 kg $CO_2$/kg waste, (OVAM 2020)

### Leakage of biobased plastic waste to the environment

The challenges with leakage of plastic waste to environment are described in section 2.2.6 of this report. There is lack of research, but the hypothesis is that biodegradable biobased plastics should reduce this problem as they eventually biodegrade rather than just degrade into long-lasting micro- and nano-plastics. It is also predicted, but lacks conclusive empirical evidence, that marketing plastic packaging or products as biodegradable/compostable could increase the tendency to litter and several studies support the perception of consumers that littering biodegradable or compostable products is less environmentally harmful. (Jakobsen 2020) Furthermore, the perceived time biodegradation takes is not aligned with the actuality.

# 4 Plastics and natural capital

## Summary and discussion

Plastics and biobased plastics have implications for several natural capital assets throughout their entire lifecycles. Biobased plastics are made from a number of different feedstocks and can have various sustainability impacts on land and water use, biodiversity, indirect greenhouse gas emissions and create competition with food production for resources. The overall impacts of biopolymers need to be thoroughly evaluated case by case as generalisation of the assumption that all biobased plastics have a lower environmental impact can be wrong.

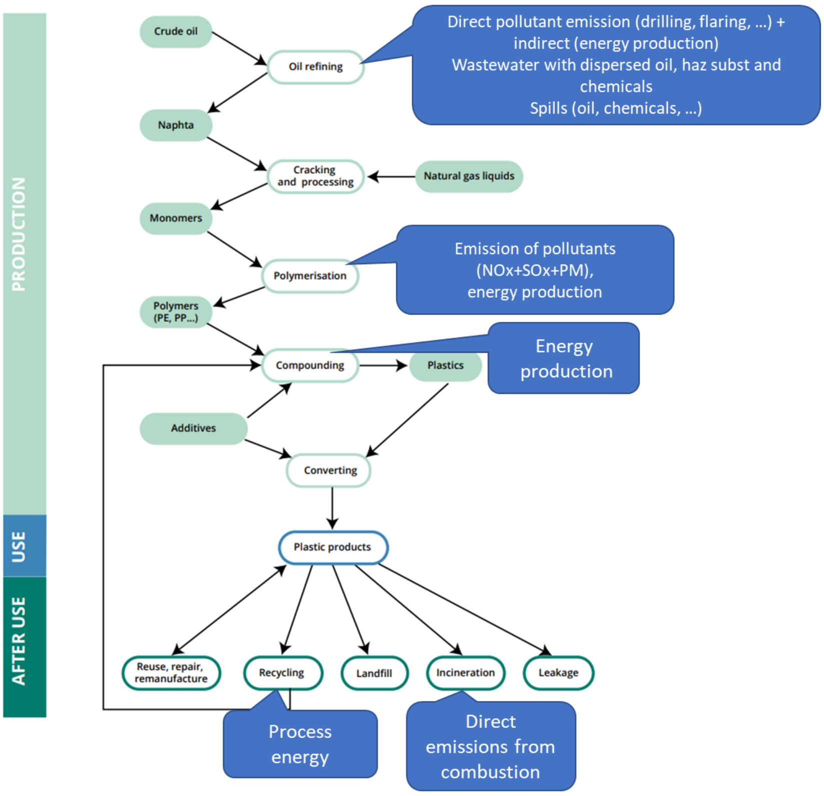
## 4.1. Introduction

Natural capital is a term used to describe the renewable and non-renewable natural resources that companies rely on to produce goods and deliver services. Indeed, one of the premises of sustainability is to preserve natural capital, meaning that renewable resources should not be used faster than they can be regenerated, resources that can be depleted should not be dissipated and lost to recovery, reuse or recycling, and waste should be avoided as it is a sign of inefficiency. Businesses depend on non-renewable natural assets, such as fossil fuels and minerals, as well as renewable goods and services, such as freshwater, timber and a stable climate. (EEA 2018; UNEP 2014).

Business and other activities such as extraction and production can damage natural capital and cause economic costs that are largely external to market prices. Similarly, the value of access to land, clean air and plants that provide critical inputs such as food, energy and fibre is usually excluded from financial accounts. Increasing environmental degradation and resource depletion combined with growing demand is highlighting the need to better understand and value natural capital (Trucost 2016).

Greenhouse gas emissions from production and after-use incineration cause the most prominent environmental impact of the plastics value chain. However, externalities related to the plastics value chain are also found in the other areas, such as degradation of natural systems as a result of resource extraction and leakage, particularly to oceans; and health and environmental impacts from various substances of concern (Figure 4-1) (EMF 2019).

*Figure 4-1 Externalities related to the plastics value chain*



**Source**: ETC WMGE

In this chapter the impact of plastics on natural capital is briefly discussed, touching upon the following topics:

- depletion of fossil resources;
- soil, water and groundwater pollution and water depletion;
- direct and indirect air pollution and emissions;
- land use and soil erosion;
- loss of biodiversity.

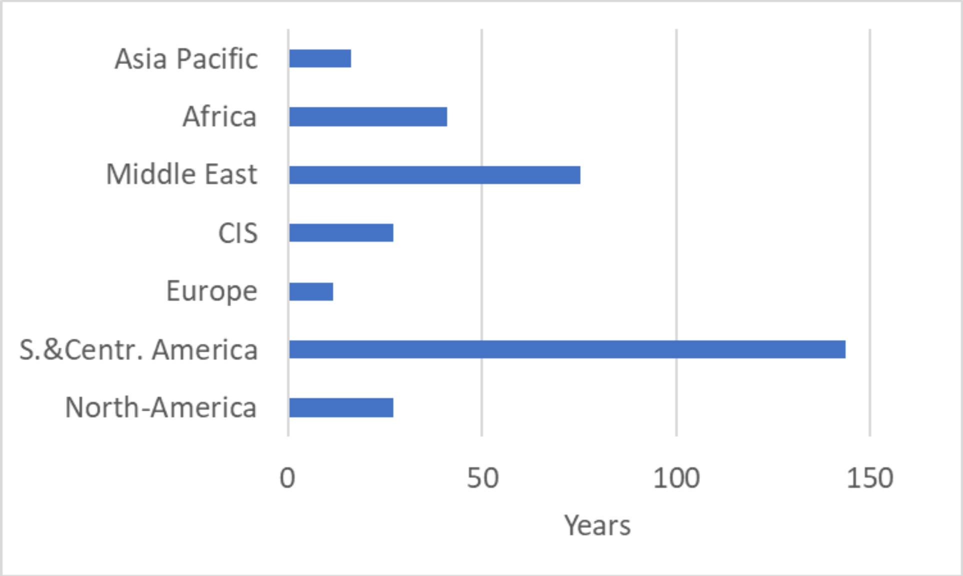
## 4.2. Depletion of fossil resources (Extraction)

The plastics industry is highly reliant on stocks of fossil oil and gas. It is estimated that 4–8 % of the world's oil production is used to make plastics (EMF 2019), roughly half of which is used as material feedstock and half as fuel for the production process (OECD/IEA, 2018). In Europe, it is estimated that between 4–6 % of oil and gas is used for producing plastics. By contrast, 87% is used for transport, electricity and heating (British Plastics Federation, 2019). Yet, if trends in oil consumption and plastic production continue as expected, the consumption of oil by the entire plastics sector will account for 20 % of the total consumption by 2050.

Global proved oil reserves were 1 734 billion barrels at the end of 2019. The top countries in terms of reserves are Venezuela, 17.5 % of global reserves; closely followed by Saudi Arabia, 17.2 %; and Canada, 9.8 % (BP 2020). The global oil consumption in 2019 reached an average of almost 100 million barrels per day, with Europe consuming an estimated 15 million barrels per day. (BP 2020)

Fossil oil reserves are finite; the global reserves/production ratio shows that known oil reserves in 2019 accounted for 50 years of current production but with significant regional differences. Europe has the lowest reserves/production ratio: only 12 years while the reserves in South and Central America could last for 144 years at current consumption rates (Figure 4-2). Since oil production is growing at the same pace as oil consumption, however, it is likely that these are over estimates unless new reserves are discovered and come on line in the coming years.

*Figure 4-2 Global known oil reserves to production ratios per region, 2019, years*



**Source**: adapted from BP (2020)

Global oil demand is expected to grow by an additional 10 million barrels per day by 2030. Petrochemicals are the largest driver of global oil consumption and are set to account for more than a third of the growth in oil demand to 2030. In this respect, the growing oil demand for petrochemicals needed for plastics production is more important than the demands for road haulage, aviation and shipping. Moreover, the importance of the current dominant source of oil demand, particularly for passenger vehicles, is fading, thanks to a combination of better fuel economy, rising public transport, alternative fuels and electrification. (IEA 2018)

The plastics sector is increasingly aware of the fact that it is exposed to the risks caused by declining fossil oil reserves (British Plastics Federation 2019) and is therefore exploring alternatives. Hydrogen and carbon, freely available in the atmosphere, are the basic building blocks for the production of plastics. The most convenient way of accessing them is by taking them out of fossil sources like oil but hydrocarbons can also be made from biomass containing starch, cellulose, sugars or lactic acid, organic waste, vegetable oils, micro-organisms and even the $CO_2$ in the atmosphere itself. Moreover, through recycling, plastic waste can be converted into feedstock, keeping carbon and hydrogen in the loop.

## 4.3. Soil, water and groundwater pollution and water depletion

Throughout the lifecycle of fossil- and bio-based plastics, there are several risks associated with soil, water and groundwater pollution as well as water depletion. Mercury emission from chlorine manufacturing for PVC is just one example of a potential water pollution problem associated with plastics production. Plastics are composed of polymers and additives and most of the chemicals used as additives, which can be harmful to the environment, are not bound in the plastic for the whole of its lifecycle but able to migrate. According to Stenmarck et al. (2017) “migration depends heavily on the physical-chemical properties of the substance depending on the substance’s size, boiling point, vapor pressure, solubility in the plastic and the environment/material surrounding the plastic”.

With bio-based plastics, the feedstock production phase causes pollution and depletion through irrigation, fertilisation, use of pesticides, and so on. Landfilling is also a direct source of pollution, while composting can result in environmental pollution through, for example, soil remediation. Macro-, micro- and nano-plastics leaking into the environment and littering are also of recent concern. A particular case of littering is the loss of plastic pellets or nurdles from production facilities. This source of plastic pollution is receiving more and more attention in recent initiatives (e.g. Operation Clean Sweep) and has indeed been identified as important in research. (Karlsson 2018)

**Landfilling**

The landfilling of plastics is a concern as it may cause chemicals contained within the plastics to become more available to leach into the environment. Additives and some plastic precursors such as bisphenol A are known to be harmful or hazardous when leached into soil and water. Some of these compounds are phthalates, including di(2-ethylhexyl) phthalate, benzylbutylphtalate, dibutyl phosphate, diisononyl phthalate, diisodecyl phthalate and di-n-octylphthalate, which are used as plasticisers. Flame retardants, such as commercial octabromodiphenyl ether, commercial pentabromodiphenyl ether and decabromodiphenyl ethane, are known to be hazardous because they contain halogenated compounds (Verma et al., 2016). Even though the use of these compounds in new materials is increasingly regulated, they still occur in the waste fractions.

Incineration of plastics can also be a source for heavy metals, persistent organic pollutants, solid residue ash and airborne particulates in the environment, animals and humans as they are transported through the atmosphere and are deposited in waters, soil and crops.

**Biodegradable plastics and composting**

Biodegradable plastics can be turned into compost and applied as a soil conditioners or fertilisers. This compost, however, can also be a source of soil, water and groundwater pollution (EEA 2020a). None of the regulations regarding compost or digestate quality at an EU or Member State level, takes the impacts of microplastics on the terrestrial environment into account or seeks to reduce them. Currently plastic contaminants less than 2 millimetres in size are allowable, larger than the definition of microplastics, which are typically less than 1 millimetre. Due to incomplete biodegradation, these plastic particles can contaminate soil but, on the other hand, little is known about the contribution of biodegradable plastics to soil quality: nutritional benefits are unclear, and research suggests that in composting at least half of compostable plastics are transformed into $CO_2$ emissions during biodegradation.

**Macro-, micro- and nano-plastics**

Since the mass production of plastics in the 1950s, global plastic waste is estimated to be 6 300 Mt, of which 79 % has accumulated in landfills and environment (Ng et al., 2018). Landfilling is also one of the main sources of plastic waste ending up and accumulating in the environment due to runoffs. Living organisms in land and sea are susceptible to the harmful effects of plastic waste in nature by mechanical irritation or through exposure to the chemicals released from plastics (Jambeck et al. 2015; Rochman et al. 2013). Studies have confirmed that there is plastic pollution from the Arctic to the Antarctic, in sediments, soil, rivers and also in the air (Prata et al. 2020).

Degradation of plastics from macro- to micro- and further into nano-particles in the environment is of recent concern due to their reported ecotoxicity and the possibility of their entering living organisms in the food chain (Astner et al., 2019; Alimi et al., 2018) Nano-particles are difficult to detect and easily transported in air, soil and water, and they also seem to be able to pass through the biomembranes of cells. The loads, transformation, transport and the environmental impact of plastics in terrestrial and subsurface environments have not been studied to the same extent as the impacts of plastic in marine environment. It is known that as the plastic particle size decreases, the possible chemical-like effects increase (Alimi et al., 2018; Piehl et al., 2018). In marine environments, micro- and nano-plastics have been connected with harming fish and other marine organisms causing lower growth, reproduction and wellness problems, and affect biodiversity. It has been estimated that agricultural soils could already hold more micro-plastics than marine systems, even 4 to 23 times as much – in a kilogram of soil, there can be more than 40 000 micro-plastic particles. (de Souza Machado et al. 2019; Machado et al. 2018)

**Water depletion**

Water used for irrigation originates from groundwater, surface waters and aquifers. The effects on freshwater resources and their sustainable use, for example, for irrigation, is very dependent on location – what the reserves are, how they are replenished, whether they are finite, but also whether natural rainfall is suffucuent or irrigation is needed (CE Delft, 2017). Water withdrawals have risen significantly as 40 % of the increased food production over the last 50 years originate from irrigated areas – the production of agricultural goods has increased 2.5 to 3 times over that period, but the agricultural land has only increased by 12 %. Globally, of all the freshwater that is withdrawn from aquifers, streams, rivers and lakes, 70 % is used for agriculture. This has led to water depletion and scarcity around the world, but especially in Asia, northern and southern Africa and western North America. Deforestation is also linked to water depletion as forests act as water regulators and also purify it (Lewandowski 2018).

## 4.4. Direct and indirect air pollution and emissions

Several different air pollution sources originate from the plastics value chain, especially from refining, polymer production, conversion and incineration. Releases of toxic chemicals include substances such as sulphur oxides, nitrous oxides, methanol, ethanol oxide, volatile organic compounds, trichloroethane, acetone, methylene chloride, methyl ethyl ketone, styrene, toluene, benzene, 1,1,1-trichloroethane, etc.

Incineration of plastic waste is one of the main sources of direct air pollution and emissions. When plastics are incinerated, toxic gases such as dioxins, furans, mercury, halogens and polychlorinated biphenyls are released into the atmosphere. Volatile organic compounds (VOCs) and semi-VOCs such as olefins, paraffin, aldehydes and light hydrocarbons are commonly released. In addition, the by-products of incineration are airborne particulates and solid residue ash, which can contain high concentrations of persistent free radicals. The harmfulness of plastic incineration depends on the type and composition of plastics incinerated and the operating conditions in which it is done, open field plastic burning, for example, is considered to be more harmful due to unoptimized incineration processes and flue gas cleaning operations. Incineration of plastic waste, especially in open fields, is one of the worst sources for toxic air pollution – in developing countries open burning is common, but in developed countries landfill fires can also occur and result in serious emissions. With complete combustion, almost 90 % of plastic waste, excluding polyvinylchloride, is reduced to carbonic acid, $CO_2$ and water (Verma et al. 2016).

Dioxins are lethal persistent organic pollutants released from incineration processes. As they settle on crops and waterways, they are able to enter the human food and water cycles. The incineration of polyvinylchloride releases hazardous halogens, dioxins, black carbon and aromatics including pyrene and chrysene into the air. Brominated flame-retardant plastics release bromine when incinerated and this can also be released during high-temperature recycling processes. These hazardous brominated compounds are carcinogenic and also act as mutagens. Incomplete incineration of plastics was found to cause high concentrations of carbon monoxide and noxious emissions (Verma et al., 2016).

## 4.5. Land use and soil erosion

Although renewable, biomass is also a limited and valuable resource, which should be used sustainably. A number of factors have to be considered for sustainable use of biomass, including environmental aspects, such as soil erosion, water shortages, use of pesticides and eutrophication due to the overuse of fertilisers, land availability, indirect land-use change and the conservation of biodiversity.

A wide variety of sectors compete for the use of biomass (Bazzanella 2017):

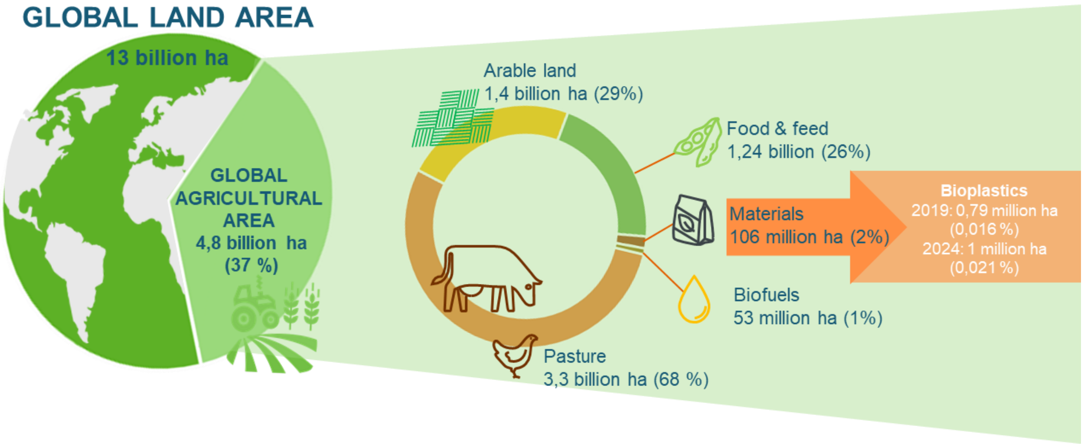
- food and feed supply: competition for sugar- and starch-containing biomass ("1st generation biomass");
- energy: large amounts of biomass are used for the generation of electricity and heat, by combustion and/or gasification;
- fuel: large amounts of renewable feedstock are used for production of biofuels;
- material and carbon feedstock: wood and paper industry, and other sectors.

It has been estimated biodiversity loss is largely driven by land conversion for agriculture and forestry.

The production of biomass for plastics can lead to both direct and indirect changes in land use. An example of direct land-use change is the conversion of tropical rainforests into sugar cane plantations for bio-based material production. Indirect land-use change is a chain effect of separate action that leads to agricultural expansion and deforestation elsewhere. An example of this is when land that was originally used to grow food for human consumption is converted to grow a crop, such as rapeseed, used for bio-based products and the food is imported from elsewhere, possibly from where forests have been converted to agricultural land to support the new demand.

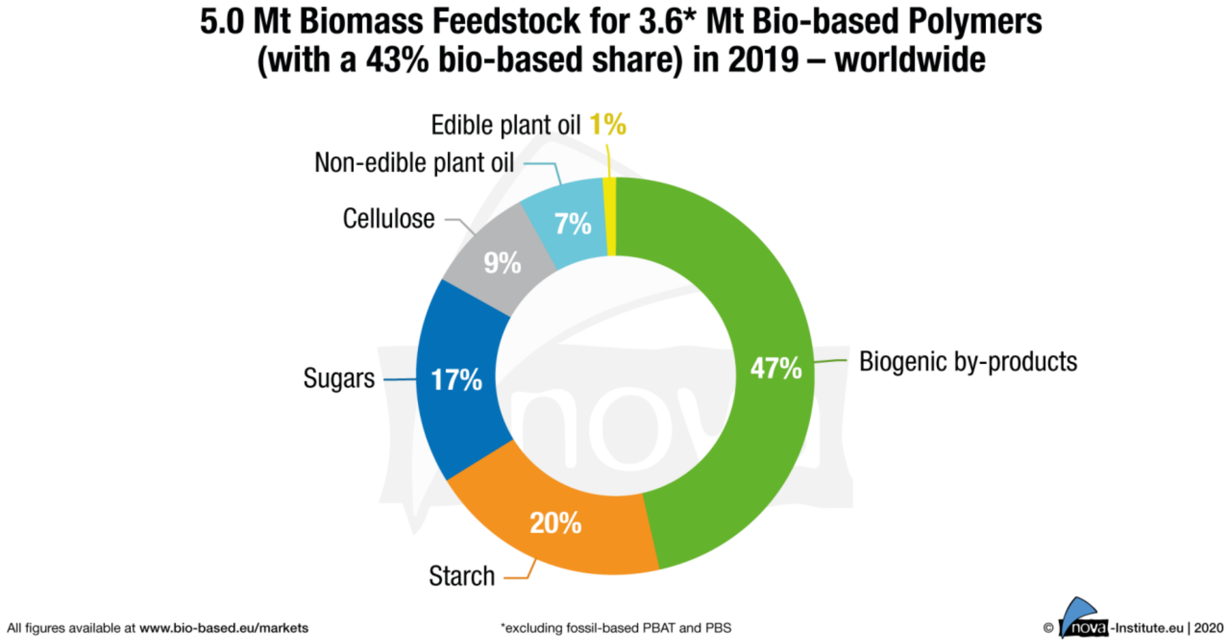
The choice of feedstock and avoiding conflicts with food production are fundamental issues for bio-based plastics. Biomass used to make bio-based plastics should not compete, directly or indirectly, with food production, and should consist of unavoidable waste biomass, such as agricultural and forestry residues of lignocellulose and food supply chain waste. Use for plastics, however, can compete with the use of the same wastes for the generation of renewable energy which is supported by the European Commission's Renewable Energy Directive (EASAC 2020). It has been calculated that if all the world's fossil plastics in 2015 had been produced from biomass, the demand for feedstock would have been be 5 % of the total amount of biomass produced and harvested (Oever et al. 2017). This does not take account of the use of side and waste streams. Figure 4-3 shows an estimate of the amount of land needed to produce biomass for biobased plastics production in 2019 and 2024 compared to that needed to meet the demand for food, feed and biofuel production.

*Figure 4-3 Estimated land use demand for biobased plastics, 2019 and 2024, hectares, per cent*



**Sources**: European Bioplastics (2019) and Nova Institut (2019)

*Figure 4-4 Biomass feedstock used to produce bio-based polymers, 2019, per cent*



**Source**: (European Bioplastics 2019) and (Nova Institut 2019)

The impact of bio-based plastics, and the bioeconomy in general, on issues such as land use, competition with food and impacts on agricultural processes as well as biodiversity have received widespread attention. Fully assessing the impact of bio-based feedstock on these issues is a complex endeavour. However, negative externalities could be reduced by applying regenerative principles that encourage the sequestration of atmospheric $CO_2$ in soil in agriculture. Applying bio-based processes to make alternative monomers are now in the pilot phase of development. In these processes, these alternative monomers, which resemble the molecules in bio-based feedstocks more closely than ethylene molecules, are produced at lower temperatures than steam cracking, thereby producing fewer emissions from fuel combustion and abating end-of-life emissions.

Soil is one of the most important non-renewable resources and one of the most complex of all ecosystems - it is a habitat in its own right, and home to a huge diversity of organisms. The organisms regulate and control key ecosystem services such as soil fertility, nutrient cycling and climate regulation. It is vital for human and economic health, as well as the production of crops and other materials and applications produced from agricultural raw materials. Intensive agriculture and deforestation have led to soil degradation – wind and water erosion are a major process that lead to physical losses of soil. Crop production using inappropriate cultivation methods leads directly and indirectly to soil degradation through erosion and compaction. The clearing of forests for agricultural purposes and land conversion for intensive cultivation lead to soil decomposition and erosion due to runoff (Lewandoski, et al. 2018). In the EU, the degradation of soil is having considerable environmental and economic consequences. Poor land management, caused by deforestation, overgrazing, unsustainable farming and forestry practices, construction activities and land sealing are among the main causes of this situation. This links strongly to the loss of biodiversity. Desertification is seen as an increasing threat in the EU.

## 4.6. Loss of biodiversity

Biodiversity loss and ecosystem collapse are two of the biggest threats facing humanity in the next decade. Specifically, biodiversity loss results in reduced crop yields and fish catches, increased economic losses from flooding and other natural hazards, and the loss of potential new resources. Healthy ecosystems also filter the air and water resources. In the last 40 years, there has been a decrease of more 60 % of global wild species populations and 1 million species are at risk of extinction. Farmland birds and insects, particularly pollinators, are key indicators of the health of agroecosystems and are vital for agricultural production, but their alarming decrease is the result of loss in biodiversity. Climate change, often seen as a separate issue, also strongly affects the loss of biodiversity (EC 2020).

Agriculture is the primary source of food and feed, and is increasingly important for the bioeconomy sector. Agriculture, however, has been identified as a significant contributor to biodiversity loss. Increased use of pesticides, herbicides and fertilisers, increased landscape homogeneity, drainage of waterlogged fields, loss of patches of marginal and uncropped habitat and reduced fallow periods are the main causes and accelerators of biodiversity loss (Lewandoski, et al. 2018).

Some of the key reasons for this are linked to chemical pesticides, especially hazardous ones. Soil erosion and desertification are also factors that affect the loss of biodiversity. In addition, deforestation and land-use changes are linked strongly to the issue.

As plastics value chains are energy intensive, the use of non-renewable energy sources is also a contributor to the loss of biodiversity. Plastic pollution of the environment is also strongly linked to the loss of biodiversity, particularly in marine ecosystems.

# 5 Conclusions

The overall greenhouse gas emissions from the EU plastics value chain for 2018 were estimated at 208 Mt $CO_2$-eq. The majority, 63 % of this, is related to resin production. Converting these polymers to products accounts for 22 %, and plastic waste treatment adds a further 15 %, mainly due to incineration. The average production of 1 tonne of plastic emits 2.9 t $CO_2$-eq, with energy supply – heat, steam and electricity – during plastic production being the major contributor. When incinerated at end of life, an additional 2.7 t $CO_2$-eq are emitted per tonne of plastics burnt ([1]).

The plastics value chain has significant untapped potential to reduce its $CO_2$ emissions due the current overall low recycling rate. The high quality recycling of plastics could be beneficial to climate impact in two ways:

- it avoids $CO_2$-emissions during incineration of the plastic waste; and
- the outputs can replace the production of primary raw materials and therefore avoid the corresponding greenhouse gas emissions.

This is relevant both for fossil- and bio-based plastics.

Switching from fossil- to bio based plastics has potential to reduce the greenhouse gas emissions of the plastic value chain, but also presents such other challenges as sustainable land use and competition with food to protect and maintain natural capital.

The current share of bio-based polymers in total plastics production at 1 % is very small. The potential of biobased plastics to reduce plastics' carbon footprint lies in sourcing because of the sequestration of $CO_2$ during the production of biological raw materials.
The energy related emissions from heat, steam and electricity production are a major contributor to $CO_2$ emissions in the value chains of both fossil- and bio-based plastics.

The value chains for specific polymers of both for fossil- and bio-based plastics are very complex and the $CO_2$ footprint varies a lot depending on the necessary raw materials, the production and utilisation of side and waste streams, as well as the different end-of-life options.

The overall yearly greenhouse gas emissions of EU's plastic demand, if based on bio-based plastics, is estimated at 146 Mt $CO_2$-eq in total, which is 62 Mt or 30 % less than the emissions for the fossil-based value chain.

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# Annex 1: LCI datasets

*Table: Resin production LCI datasets – further description.*

| Dataset (Ecoinvent 3.6) | Description |
|---|---|
| Polypropylene, granulate (RER) production | For polypropylene, the dataset represents mix of commercial PP production technologies: slurry suspension polymerization, bulk suspension polymerization, and gas phase polymerization using catalysts. Suspension polymerisation can be described as a precipitation process. The formation of the polymer takes place in a hydrocarbon diluent and under conditions where the monomer is soluble in the solution. The precipitated polymer is separated from the suspension by centrifugation. The suspension process can be combined with a stirred tank reactor or a loop reactor. After polymerisation the polymer is usually fed directly into a hot melt extruder, where additives can be added to the melted polymer if required. The polymer is then pelletised in an underwater pelletiser. The pelletised product is dried, blended where required and degassed.<br>In the gas phase processes a fluidized bed of polymer particles and catalyst is maintained by a steady gaseous monomer feed from the bottom of the reactor. Polymer powder is continuously extracted at the bottom of the fluidized bed reactor. |
| Polyethylene, low density, granulate (RER) production<br>Polyethylene, high density, granulate (RER) production | The dataset represents the production mix of commercial LDPE production technologies: high pressure polymerization using oxygen and/or organic peroxide as initiator. High pressure polymerization is carried out at pressures of 1500 to 3500 bar and temperatures of about 200°C. The reaction may take place either in an autoclave or a tubular reactor. The polymerisation is an exothermic reaction . The ethylene gas is used as a heat sink for the resulting heat. The heat of the exothermic reaction can also be recuperated to generate low pressure steam. After polymerization, the polymer is usually fed directly into a hot melt extruder, where additives can be added to the melted polymer if required. The polymer is then pelletised in an underwater pelletiser. The pelletised product is dried, blended where required and degassed. |
| Polyvinylchloride bulk polymerised (RER) production | European dataset is a compilation of global datasets for emulsion polymerized PVC (12,7%) and suspension polymerized PVC (87,2%). |
| Polyurethane, flexible foam (RER) production<br>Polyurethane, rigid foam (RER) production | PUR flexible foam: dataset represents the production of 1 kg of one possible composition of PUR flexible foam. PUR flexible foam is used for manufacturing products such as mattresses, cushions and car seats. This dataset models the producton of PUR foam from polyols and toluene diisocyanate. The inventory is estimated based on industrial data. The dataset doesn't include solvents and additives required for the production of PUR.<br>PUR rigid foam: the dataset represents just one possible composition for rigid PUR foam. The inventory is modeled for Europe. |
| Polyethylene terephthalate, granulate, amorphous (RER) production | Data are based on the average unit process from the Eco-profiles of the European plastics industry. These average data represent the production of amorphous PET out of ethylene glycol and PTA. The data include material and energy input, waste as well as air and water emissions. The inventory is modelled for Europe. |
| Polystyrene, general purpose (RER) production<br>Polystyrene, high impact (RER) production | Data are derived from the Eco-profiles of the European plastics industry (Plastics Europe). The inventory is modelled for Europe. Polymerization out of ethylene and benzene by free radical process.<br>Data are derived from the Eco-profiles of the European plastics industry (Plastics Europe). The inventory is modelled for Europe. Polymerization out of ethylene and benzene by free radical process. |

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