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Climate Impact of Primary Plastic Production

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Climate Impact of Primary Plastic Production

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Abstract

Plastics show the strongest production growth of all bulk materials over the last decade. The industry's current growth trajectory is exponential and plastic production is expected to double or triple by 2050. The rapidly increasing production of plastics and the continued reliance on fossil fuels for production, have contributed to numerous environmental problems and health harms. As a result, plastic pollution has become an increasing threat to natural ecosystems, human health and climate. However, there is a lack of granularity on the contribution of the primary plastics specifically to greenhouse gas (GHG) emissions and their impact on the remaining global carbon budget needed to stay below a 1.5°C or 2°C global average temperature rise. In this report, we explore the contribution of primary plastic production to climate change disaggregated by polymer and technology. To this end, we have developed comprehensive bottom-up modeling of GHG emissions from global primary plastic production, with a special focus on polymer value chains. We have analyzed the results under various growth scenarios in the context of carbon budgets compatible with a 1.5°C global trajectory. Modeling includes the material flows of all production stages, processes and technologies used in primary plastic production value chains, including from the extraction of fossil fuels required for production to shaping the final product. We specifically focus on nine major types of fossil fuel-based plastic polymers that are produced and consumed in large quantities: three types of polyethylene (PE) – low-density (LDPE), linear low-density (LLDPE), and high-density (HDPE) – as well as polypropylene (PP); polyethylene terephthalate (PET); polyvinyl chloride (PVC); polystyrene (PS) and other key styrene-based plastics such as styrene acrylonitrile (SAN) and acrylonitrile butadiene styrene (ABS), and polyurethane (PU). Together these account for about 80% of plastics production.

Our estimates show that global production of primary plastics generated about 2.24 gigatonnes of carbon dioxide equivalent (GtCO$_2$e) in 2019, representing 5.3% of total global GHG emissions (excluding, agriculture and LULUCF (Land Use, Land-Use Change and Forestry)). Emissions from primary plastic production are generated from the combustion of fossil fuels for process heat and electricity and from other non-combustion processes. Approximately 22%, 21%, and 15% of emissions related to primary plastic production in 2019 come from all PEs together, PET, and PP, respectively. Other key plastics, i.e., PVC, PS, SAN, ABS, and PU are responsible for around 23% of global emissions from plastic production. Most (~75%) GHG emissions from primary plastic production occur from the steps prior to polymerization. Under a conservative growth scenario (2.5%/yr), GHG emissions from primary plastic production would more than double to 4.75 GtCO$_2$e by 2050, accounting for 21-26% of the remaining global carbon budget to keep average temperature increases below 1.5°C. At 4%/yr growth, emissions from primary plastic production would increase more than three times to 6.78 GtCO$_2$e, accounting for 25-31% of the remaining global carbon budget for limiting global warming to 1.5°C.

Such detailed modeling of individual primary plastic polymers, where production value chain stages are fully taken into account, can provide a sound technically neutral and scientific foundation to inform the global plastic treaty and enable stronger coordination with other global treaties on climate change (e.g., United Nations Framework Convention on Climate Change (UNFCCC)). [1] Such modeling is also critical to understand the climate impacts of proposed mitigation measures under the treaty, as most of these are either polymer-specific or would have different implications per polymer.

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[1] UNEP/EA.5/Res.14. entitled "End plastic pollution: towards an international legally binding instrument" – also referred to as the global plastics treaty.

Executive summary

Annual global production and demand for plastics, including elastomers and fibers, reached about 460 million metric tonnes (Mt) in 2019, having experienced an average annual growth rate of 3.6% since 2000 [1]. The rapidly increasing production of plastics and the continued reliance on fossil fuels for feedstocks (i.e., raw materials) and process energy (i.e., energy required for process heat and electricity), have contributed to numerous environmental problems and health harms [2,3]. As a result, plastic pollution has become an increasing threat to natural ecosystems, human health and climate. In recognition of this, 175 nations endorsed resolution 5/14 at the fifth Session of the United Nations Environment Assembly (UNEA) in March 2022 to end plastic pollution with the aim of developing an international legally binding instrument (ILBI) by 2024 – also referred to as the global plastics treaty.[2]

However, while resolution 5/14 acknowledges the impacts of plastic production on the triple planetary crisis of climate change, biodiversity loss, and pollution, proposed efforts to reduce plastic pollution do not yet include any explicit consideration of climate impacts. At the same time, there is limited recognition of the significant contributions of plastic production to climate change in the UNFCCC (United Nations Framework Convention on Climate Change) climate negotiations. The recent Intergovernmental Panel on Climate Change (IPCC) Assessment Report made it clear that without an immediate reduction of GHG emissions, the mean global temperature is likely to increase by more than 1.5°C above pre-industrial levels by 2050 with severe consequences across the planet [4]. Avoiding devastating climate change requires rapid actions in every sector on a global scale, including plastic production [5]. This starts with a more granular understanding of greenhouse gas (GHG) emissions from primary plastic production.

This report presents an analysis that estimates the GHG emissions from primary plastic production and highlights its significant impact on climate change. It provides a science-based, technically neutral, and transparent foundation to inform negotiations on the development of a global plastic treaty and under the UNFCCC framework. We have developed comprehensive bottom-up modeling of GHG emissions from global primary plastic production, with a special focus on plastic polymer value chains, including all production stages (from extraction of fossil fuels to shaping of the final product), processes and technologies used in polymer production value chains. [3] In addition to carbon dioxide (CO_2) emissions, our modeling also accounts for non-CO_2 emissions such as methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. Such detailed modeling of individual plastic polymers, where production value chain stages are fully considered, provides more granular and accurate estimates of GHG emissions from global primary plastic production. Such modeling is critical to informing the global plastics treaty since most mitigation strategies emphasized in the treaty process are either polymer-specific or would

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[2] See UNEP/EA.5/Res.14. entitled "End plastic pollution: towards an international legally binding instrument" for more information.

[3] This study focuses only on primary plastics produced from fossil fuel-based feedstocks, and excludes bio-based and recycled plastic production. Bio-based plastic and recycled plastic constitute 1% and 6.3% of total plastic production, respectively [1,6]. However, current investments in expanded primary plastic production facilities are consistent with historical growth trends [7]. In this study, "primary plastics" refers to the synthetic plastics in primary forms, also known as virgin plastics.
In addition, the modelling and results provided in this study do not go beyond plastic production and do not evaluate GHG emission impact from the use and end-of-life stages.

have different implications per polymer, and can further enable better coordination with other global treaties on climate change (e.g., UNFCCC).

We specifically focus on modeling nine major types of plastic polymers that are produced and consumed in large quantities: three types of polyethylene (PE) – low-density (LDPE), linear low-density (LLDPE), and high-density (HDPE) – ; polypropylene (PP); polyethylene terephthalate (PET); polyvinyl chloride (PVC); polystyrene (PS) and other key styrene-based plastics such as styrene acrylonitrile (SAN) and acrylonitrile butadiene styrene (ABS), and polyurethane (PU) — which collectively account for almost 80% of the current plastic demand (Figure ES-1) [1].
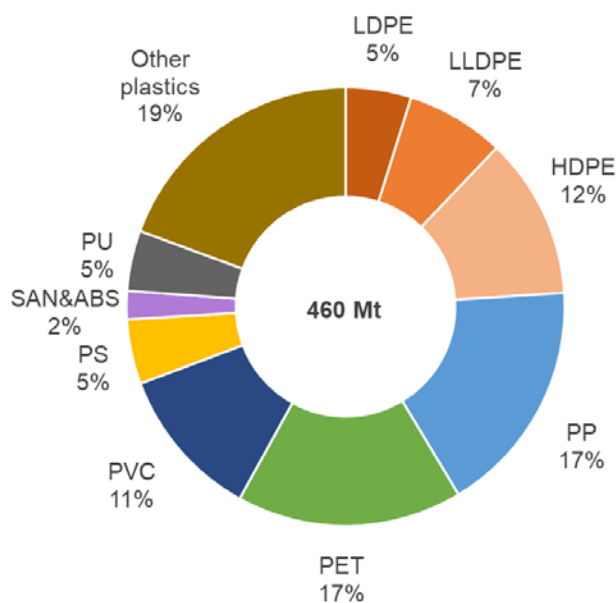
Figure ES- 1. Distribution of global plastic production by plastic polymer in 2019.

Notes: LDPE = low-density polyethylene, LLDPE = linear low-density polyethylene, HDPE = high-density polyethylene, PP = polypropylene, PET = polyethylene terephthalate, PVC = polyvinyl chloride, PS = polystyrene, SAN = styrene acrylonitrile, ABS = acrylonitrile butadiene styrene, PU = polyurethane. PET in the chart includes polyester fibers in addition to films and other PET products used for packaging such as PET bottles. PP in chart includes PP fibers in addition to other PP use cases. "Other plastics" include other plastic types such as polyamide, acrylic, and rest of the synthetic fibers, polycarbonate, elastomers other than PU, etc.
Source: [1]

The plastic industry's current growth trajectory is exponential and plastic production is expected to double or triple by 2050 [7]. In this report, we explore the total GHG emissions and carbon budget impact from 2019 through 2050 under three main business-as-usual (BAU) scenarios based on three sets of plastic production growth assumptions and assuming the power grid remains constant. The scenarios reflect continuing the current trends in production and recycling, and assume the current primary plastic production technology portfolio, recycling rate, and the global power sector remain unchanged during the modeling period. To assess the potential impact of electric grid decarbonization, three additional scenarios showing BAU with a decarbonized power grid were used (see Table ES-1 for details). These scenarios do not necessarily present likely projections; instead, they are designed to demonstrate the potential

GHG emissions impact of primary plastic production if the current production structure and consumption trends stay unchanged.

Table ES- 1. BAU scenarios used in this report

	Annual production growth [1]	Global CO$_2$ emission intensity of electricity generation [2]
BAU with constant power grid scenarios:		
BAU: No growth	No growth	Constant at current levels between 2022 and 2050
BAU: 2.5% growth	2.5% per year	
BAU: 4% growth	4% per year	
BAU with decarbonized power grid scenarios:		
BAU with decarbonized grid: No growth	No growth	Decarbonized grid between 2022 and 2050 in response to stated power sector-specific policies and targets, based on IEA [
BAU with decarbonized grid: 2.5% growth	2.5% per year	
BAU with decarbonized grid: 4% growth	4% per year	

Notes: (1) In this analysis, we do not model plastic production growth, but instead scale our GHG emissions analysis based on two different demand growth projections from two different sources (OECD [1] and NASEM [8] reports). The OECD outlook provides individual growth trajectories ranging from 2-2.8% per plastic polymer, with an average growth of 2.5% in total plastic demand between 2019 and 2050. The NASEM report estimates the annual growth of total plastic demand without any polymer details. Please see the main report for the details of the polymer specific production growth rates. (2) Global CO$_2$ emission intensity of electricity generation is based on average global grid CO$_2$ emission intensity factors from IEA World Energy Outlook [9]. BAU = Business-As-Usual.

Key findings

Plastic production significantly impacts the climate. Our estimates show that GHG emissions from plastic production (from extraction of fossil fuels to shaping of the final product) could amount to the equivalent of 2.24 GtCO$_2$e in 2019, representing 5.3% of total global GHG emissions (excluding agriculture and land use, land-use change and forestry (LULUCF)).[4] In comparison, the global aviation sector generated 0.6 GtCO$_2$ of CO$_2$ emissions in 2019, while the global transport sector, including aviation, generated a total of 8.3 GtCO$_2$ in 2019 [11]. By polymer type, approximately 22%, 21%, and 15% of emissions related to plastic production in 2019 come from all PEs together, PET, and PP, respectively (Figure ES-2). Other key plastics, i.e., PVC, PS, SAN, ABS, and PU are together responsible for around 23% of global emissions from plastic production. This result is based on global production volumes and differentiated emission intensities of specific processes included in the production value chain for each of the nine major plastic types.

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[4] GHG emissions across the plastic polymer value chains are quantified as CO$_2$-equivalents (CO$_2$e) using 100-year Global Warming Potential (GWP-100) values from IPCC's Sixth Assessment Report (AR6) [4]. Global GHG emissions (excl., agriculture and land use change) was 42.4 GtCO2e in 2019 [10].
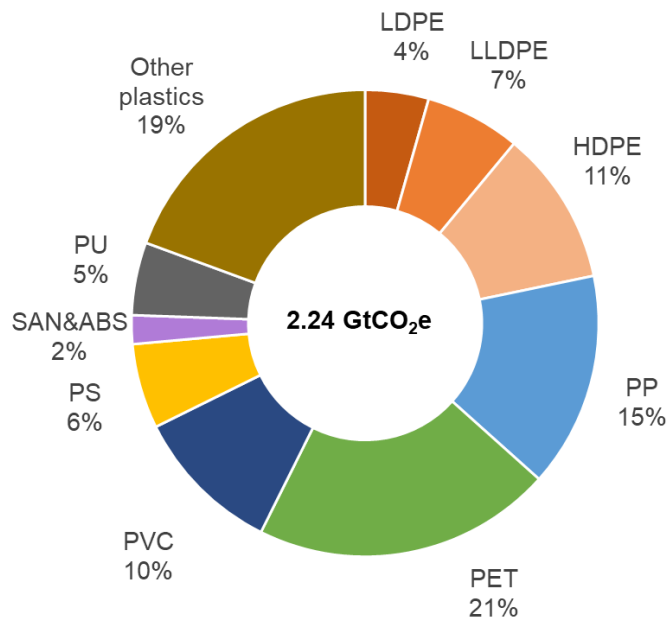
Figure ES- 2. GHG emissions from primary plastic production by plastic polymer type in 2019.

Notes: LDPE = low-density polyethylene, LLDPE = linear low-density polyethylene, HDPE = high-density polyethylene, PP = polypropylene, PET = polyethylene terephthalate, PVC = polyvinyl chloride, PS = polystyrene, SAN = styrene acrylonitrile, ABS = acrylonitrile butadiene styrene, PU = polyurethane.

Another important aspect is the contribution of production stages to total GHG emissions from primary plastic production. We find that most (~75%) emissions from plastic production occur from the steps prior to polymerization (Figure ES-3). Emissions stem primarily from the production of monomers, hydrocarbons, and non-hydrocarbon chemicals. More than a quarter (26%) of emissions are generated during monomer making (e.g., ethylene, propylene, purified terephthalic acid (PTA), vinyl chloride monomer (VCM), and styrene). Slightly more (29%) are generated from the refining of hydrocarbons (e.g., naphtha, ethane, toluene, and p-xylene) and production of other non-hydrocarbon chemicals (e.g., methanol, ammonia, and chlorine), while 20% of emissions come from the extraction of fossil fuels needed for feedstock and process energy demand of plastic production.

Primary plastic production

20% of GHG emissions	16% of GHG emissions	13% of GHG emissions	26% of GHG emissions	8% of GHG emissions	17% of GHG emissions

Extraction and/or mining *(of fossil fuels)*	Hydrocarbon refining and processing	Other chemicals production *(non-hydrocarbon)*	Monomer production	Polymerization	Product shaping
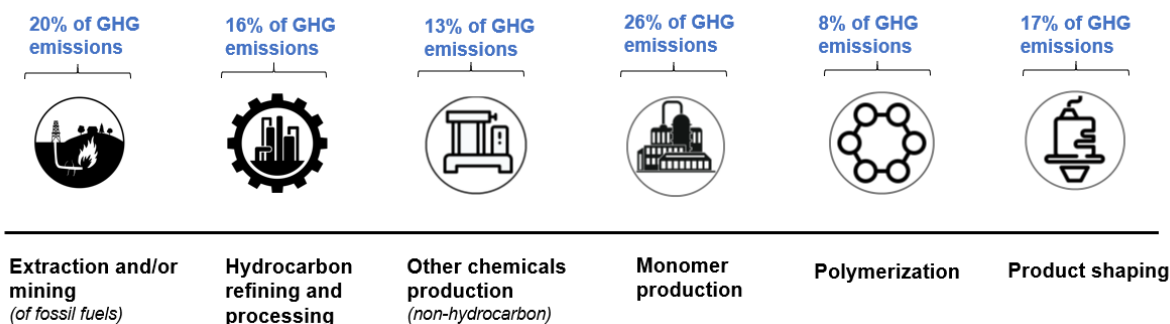
Figure ES- 3. GHG emissions shares of plastic production stages in 2019.

Notes: In this analysis, "Extraction and/or mining" refers to fossil fuel (i.e., crude oil, natural gas, and coal) extraction and/or mining step. "Hydrocarbon production" refers to refining and processing of fossil fuels for hydrocarbons (e.g., naphtha and ethane) used for the production of monomers. "Other chemicals production" refers to production of non-hydrocarbon materials (e.g., acetic acid, formaldehyde, and chlorine) used for the production of some monomers. "Monomer production" refers to the production of monomers (e.g., ethylene and propylene), which are the building blocks of polymers. "Polymerization" describes the process by which monomers are chemically combined to form larger molecules called polymers (e.g., polyethylene (PE) and polypropylene (PP)). "Product shaping" refers to the stage where polymers are processed and transformed into final products.

Figure ES-4 shows our estimates of GHG emissions from global plastic between 2019 and 2050 under the three main BAU scenarios with a constant power grid. Our estimates show that

- GHG emissions from primary plastic production could more than double by 2050, to 4.75 $GtCO_2e$ under the growth scenario of 2.5%/yr; or almost triple by 2050, to 6.78 $GtCO_2e$ under the growth scenario of 4%/yr.
- Under these two growth scenarios, cumulative GHG emissions from primary plastic production could amount to 106-126.6 $GtCO_2e$ between 2019 and 2050, equivalent to 21-25% of the remaining carbon budget that offers a 50% chance of staying below the 1.5°C threshold (Table ES-2).[5]
- Primary plastics' share of the carbon budget increases to 26-31% when considering a smaller carbon budget that offers a 67% chance of staying below the 1.5°C threshold (Table ES-2).
- If production levels remained constant from 2025 onward (i.e., No growth), primary plastic production would still account for 15% and 19% of these carbon budgets, respectively.

Under the BAU scenarios with decarbonized electric grid, GHG emissions drop to about 3.59 $GtCO_2e$ and 5.13 $GtCO_2e$ in 2050 under 2.5%/yr and 4%/yr plastic production growth, respectively. While the decarbonized grid would lead to 25% less GHG emissions in 2050, GHG emissions from primary plastic production remain high. Nonetheless, cumulative GHG emissions from primary plastic production could still account for 17-21% and 22-26% of the remaining carbon budget that offers a 50% and 67% chance of staying below the 1.5°C threshold,

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[5] The remaining carbon budget is the net amount of carbon dioxide (CO_2) humans can still emit while keeping global warming below a given limit with a given probability, taking into account the effect of other anthropogenic climate forcers [4].

respectively (Table ES-2). In addition, under a constant plastic production scenario with decarbonized grid, primary plastic production could still account for 13% and 16% of these carbon budgets, respectively.
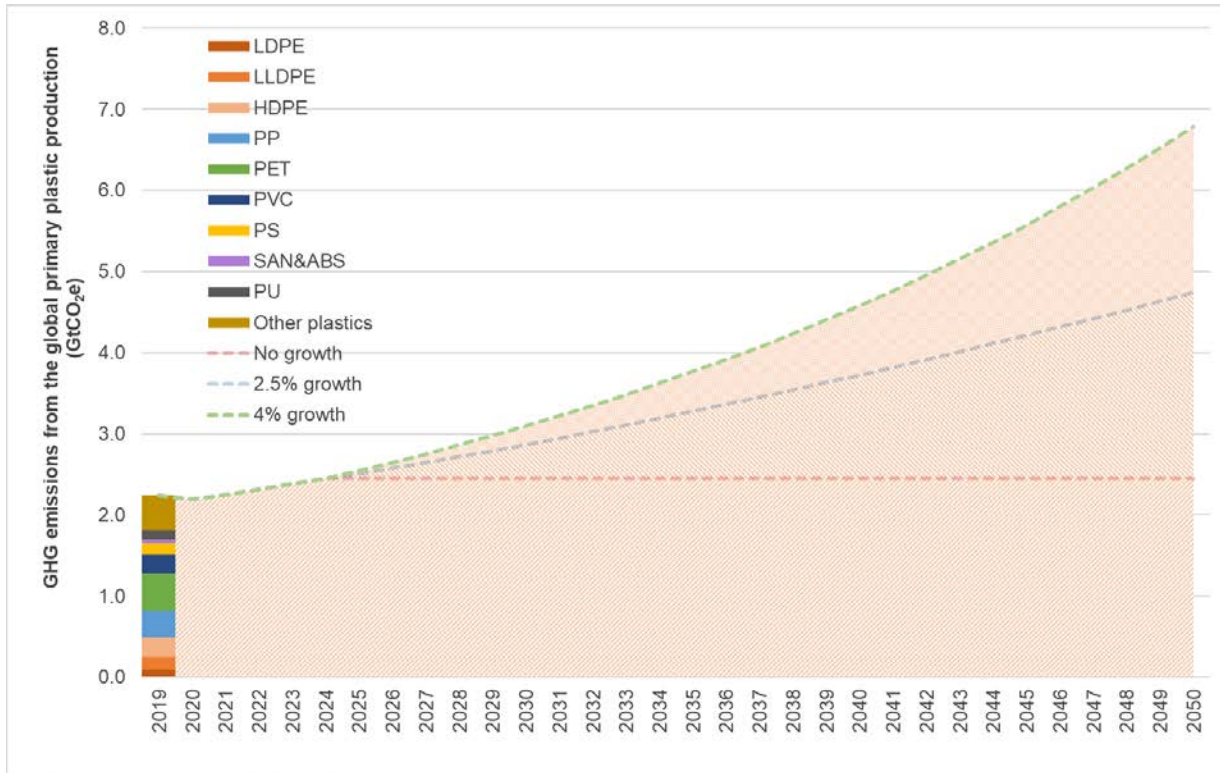
Figure ES- 4. GHG emissions from global primary plastic production between 2019 and 2050 under BAU No growth, 2.5% growth, and 4% growth scenarios.

Notes: LDPE = low-density polyethylene, LLDPE = linear low-density polyethylene, HDPE = high-density polyethylene, PP = polypropylene, PET = polyethylene terephthalate, PVC = polyvinyl chloride, PS = polystyrene, SAN = styrene acrylonitrile, ABS = acrylonitrile butadiene styrene, PU = polyurethane. Please refer to the main text for BAU with decarbonized grid scenario results.

Table ES- 2. Cumulative GHG emissions from global primary plastic production and associated carbon budget impact by 2050 under No growth, 2.5% growth, and 4% growth scenarios.

	Cumulative GHG emissions between 2019 and 2050 (GtCO₂e)	50% chance of staying below the 1.5°C temperature increase by 2050	67% chance of staying below the 1.5°C temperature increase by 2050
BAU with constant power grid through 2050			
BAU: No growth	77.4	15%	19%
BAU: 2.5% growth	106.0	21%	26%
BAU: 4% growth	126.6	25%	31%
BAU with decarbonized power grid through 2050			
BAU with decarbonized grid: No growth	66.1	13%	16%

BAU with decarbonized grid: 2.5% growth	88.7	17%	22%
BAU with decarbonized grid: 4% growth	105.0	21%	26%

Notes: Current central estimate of the remaining carbon budget from 2020 onwards for limiting warming to 1.5°C by 2050 with a probability of 50% has been assessed as 500 GtCO₂e, and for limiting warming to 1.5°C by 2050 with a probability of 67% has been assessed as 400 GtCO₂e [4]. In the table, carbon budget shares are estimated to with the cumulative emission from global primary plastic production between 2020 and 2050.

In addition, plastic production currently relies heavily on fossil fuels.[6] We estimate that global plastic production today accounts for around 12% of total demand for oil and 8.5% of total demand for natural gas. As much as 70% of this fossil fuel input is consumed as feedstock – the raw material inputs that are used as building blocks of the final plastic products – with the rest consumed as process energy, for generating heat and electricity.[7] Coal is also used in plastic production as a feedstock through methanol-based olefin, such as ethylene and propylene, but it has a much smaller share than oil and natural gas. This indicates that even with a broader portfolio of energy system decarbonization efforts towards net zero emission commitments, future primary plastic production may still be heavily dependent on fossil fuels for feedstock.

The global plastic treaty presents a historic opportunity to tackle the plastic pollution and also provide a level playing field to design upstream and downstream policies and measures to address GHG emissions from the primary plastic production globally and at scale. In achieving the overall 1.5°C goal, it is vital to set targets for the growing plastics industry that are coordinated and scalable in the context of a broader national, regional, or international political process.

In addition, most plastic pollution mitigation strategies emphasized in the treaty process thus far (e.g., production reduction, elimination of problematic polymers, and recycling) could have different climate change indications, and should be rigorously investigated from a climate perspective before a firm conclusion can be drawn about their climate impact. For example, climate impact of production reduction would vary depending on what (i.e., polymer and/or application) and how (e.g., elimination of non-essential use of plastics without an alternative, reuse, recycling, and application of alternative materials) the production is reduced. Eliminating non-essential use of plastics without alternatives, such as microbeads in cleaning products, could lead to a reduction in global GHG emissions due to a reduction in primary plastic production volume. However, the net GHG impact could be different if primary plastic production is reduced by using alternative materials or recycling. For instance, mechanical recycling can lead to GHG emissions reductions but is not applicable to all plastic polymer types. It is mostly used for PET and PE products [1], but collection, contamination, and sorting are challenges that can significantly lower the recycling efficiency [12]. In addition, the quality of the polymer often degrades with repeated recycling, so the final product may not provide the same functionality, limiting recycling to a few cycles. [12]. Some chemical recycling processes use chemical

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[6] Nearly 99% of primary plastic polymers are made from fossil-based feedstock [1].

[7] Fossil fuel input calculations (1) are based on final energy consumption and do not include fossil fuels combusted for electricity generation, (2) do not cover fossil fuels consumed during the extraction and mining stage. GHG emissions from the "extraction and mining" stage is based on global GHG emissions intensity, not energy intensity. Please see main text for modeling of the "extraction and/or mining" stage.

processes to recover the petrochemical components in plastics, e.g., monomers and hydrocarbons, and some processes convert plastics to fuels. In order for these products to be converted back into plastic polymers, they must go through additional production stages that increase their carbon footprint. Additionally, current chemical recycling methods can require higher energy inputs than mechanical recycling [13]. Similarly, certain alternative materials to plastics can increase overall GHG emissions when produced through conventional (rather than decarbonized) processes. Alternative materials used also need to be recyclable in a sustainable and climate-friendly manner. Designing products with reuse, repair and remanufacturing in mind is another important consideration to reduce climate impacts.

There is a need to design strategies with system-wide thinking to ensure that any set of solutions is circular, sustainable, and responsible and do not pose health risks. These demand and supply-side strategies need to consider implications from plastics pollution beyond climate to address environmental and health problems related to plastic from global and local perspectives. Synergistic actions between global treaties are necessary to maximize the beneficial impacts of global negotiations to end the multifaceted challenges presented by plastics and climate change.

For future work, we plan to expand our modeling framework to include recycling methods and the production of alternative materials to plastic in order to evaluate the climate impact of various mitigation strategies that may include these actions. We also plan to extend the modelling from global scale to incorporate regional details as the improved geographic granularity could help better inform the setting of region or national goals and actions.

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1. Introduction

Plastics, a suite of synthetic polymers mostly made from fossil fuel-based feedstocks (i.e., raw materials), have become widespread in modern life since the plastics industry emerged in the mid-20th century. With appealing characteristics –including versatility, durability, flexibility, and low production cost – plastics have evolved to fill a wide range of everyday end-use application such as packaging, construction, and other consumer products. As a result, global plastic production has grown at an average of nearly 9% per year since 1950, far exceeding any other industry [1,2].

Annual global production for plastics, including elastomers and fibers, reached about 460 million metric tonnes (Mt) in 2019, having experienced an average annual growth rate of 3.6% since 2000 [3]. Nine major types of plastics are produced and consumed in large quantities (see Table 1 for details). These include three types of polyethylene (PE) – low-density (LDPE), linear low-density (LLDPE), and high-density (HDPE) –; polypropylene (PP); polyethylene terephthalate (PET); polyvinyl chloride (PVC); polystyrene (PS) and other key styrene-based plastics such as styrene acrylonitrile (SAN) and acrylonitrile butadiene styrene (ABS), and polyurethane (PU) — which collectively account for almost 80% of the current plastic demand [3]. Packaging, construction, and transportation sectors are the top three end-uses for plastic products, accounting for about 31%, 16%, and 14% of total demand in 2019 [3]. Most packaging applications have short lifetimes of less than a year [4]. Construction and transportation products last longer. The average period for infrastructure and buildings is close to 40 years, and for vehicles it is between 15 and 30 years [4,5]. Segment-specific demand patterns may differ at particular points in time (e.g., when the Covid-19 pandemic impacted packaging). Figure 1 shows the shares of plastic polymers and main application of plastic products in 2019.

Table 1. Nine key plastic polymer types commonly used

Plastic	Abbreviation	Type [1]	Key end uses
Low-Density Polyethylene	LDPE	Thermoplastic	Packaging, consumer products, and construction
Linear Low-Density Polyethylene	LLDPE	Thermoplastic	Packaging, consumer products, and construction
High-Density Polyethylene	HDPE	Thermoplastic	Packaging, consumer products, and construction
Polypropylene	PP	Thermoplastic	Packaging, consumer products, and construction
Polyethylene terephthalate	PET	Thermoplastic	Packaging and textile
Polyvinyl chloride	PVC	Thermoplastic	Construction
Polystyrene	PS	Thermoplastic	Packaging, consumer products, and construction
Styrene Acrylonitrile and Acrylonitrile Butadiene Styrene	SAN and ABS	Thermoplastic	Consumer products, construction, and electrical and electronic equipment
Polyurethane	PU	Thermoset	Consumer products, construction, and vehicles

Notes: (1) Based on the characteristics of the final plastic polymers, plastics are grouped into two primary families: "thermoplastics" and "thermosets" [2]. Thermoplastics are the plastic polymers that soften to show fluid behavior

when heated [6]. Thermoset plastic polymers react to become permanently rigid when heated or mixed with a catalyst [6].
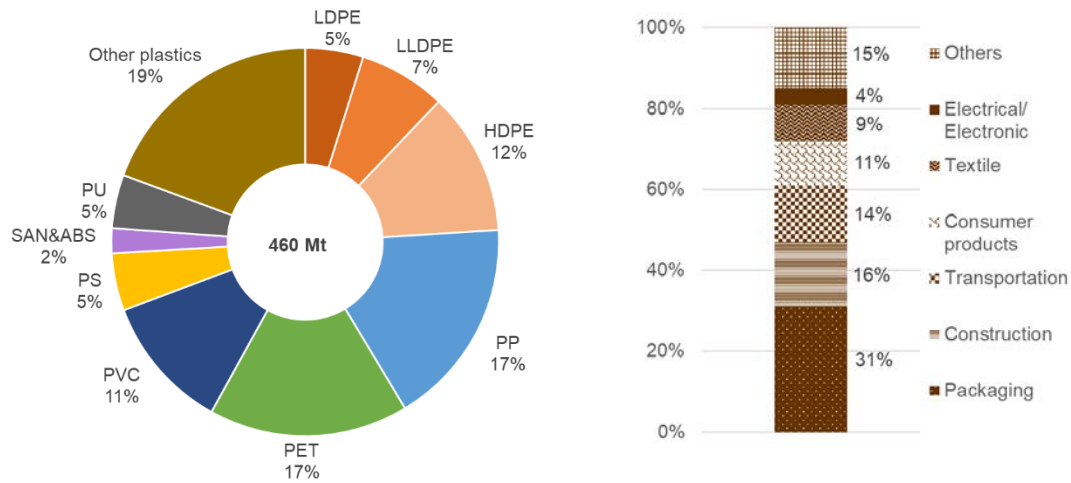
Figure 1. Distribution of global plastic production by polymer and application type in 2019.

Notes: LDPE = low-density polyethylene, LLDPE = linear low-density polyethylene, HDPE = high-density polyethylene, PP = polypropylene, PET = polyethylene terephthalate, PVC = polyvinyl chloride, PS = polystyrene, SAN = styrene acrylonitrile, ABS = acrylonitrile butadiene styrene, PU = polyurethane.

PET in the chart includes polyester fibers in addition to films and other PET products used for packaging such as PET bottles. PP in chart includes PP fibers in addition to other PP use cases. "Other plastics" include other plastic types such as polyamide, acrylic, acetate, and rest of the fibers, polycarbonate, etc. "Transportation" includes cars, ships, airplanes, and so on. See Appendix Figure A.1. for polymer specific use case information.
Source: [3]

Nearly 99% of primary plastic polymers are made from fossil-based feedstock (i.e., crude oil, natural gas, and coal) [7]. There has been a regional shift of plastic production over recent decades, with growth in the Middle East (doubled output), China (quadrupled output), and Southeast Asia since 2000 [8]. China has become the world's largest producer of plastics, accounting for nearly one-third of global production. This geographic shift has also led to growth in coal-based feedstock production in China (through methanol-based olefin production) and crude oil-based feedstock production in Europe, primarily naphtha, whereas natural gas condensates or natural gas liquids (NGL), primarily ethane, have underlain expansion in the Middle East and developments in North America [8]. Production of plastics is projected to continue rising. Estimates indicate that plastic production will grow between 2.5% and 4% annually through 2050 [3,9]. Global production of plastics could therefore reach roughly 1,000 to 1,400 Mt by 2050, a 2 to 3-fold increase from 2019 levels [3,9].

The rapidly increasing production of plastics and the continued reliance on fossil fuels for feedstocks (i.e., raw materials) and process energy (i.e., energy required for process heat and electricity), have contributed to numerous environmental problems and health harms [10-16]. These include pollution and health risks by exposure to chemicals of concern such as phthalates, bisphenols, endocrine-disrupting and carcinogenic chemicals, and "forever chemicals" (Per- and polyfluoroalkyl substances (PFAs)) used in production of primary plastic polymers; plastic particle pollution (particularly in the marine environment) and related biodiversity loss; and

climate change. As a result, plastic pollution has become an increasing threat to natural ecosystems, human health and climate. In recognition of this, 175 nations endorsed resolution 5/14 at the fifth Session of the United Nations Environment Assembly (UNEA) in March 2022 to end plastic pollution with the aim of developing an international legally binding instrument (ILBI) by 2024 – also referred to as the global plastics treaty.[1] The resolution established an Intergovernmental Negotiating Committee (INC) to draft the agreement reflecting diverse actions to address problems related to the full lifecycle of plastics. However, while resolution 5/14 acknowledges the impacts of plastic production on the triple planetary crisis of climate change, biodiversity loss, and pollution, proposed efforts to reduce plastic pollution do not yet include any explicit consideration of climate impacts. At the same time, there is limited recognition of the significant contributions of plastic production to climate change in the UNFCCC (United Nations Framework Convention on Climate Change) climate negotiations.

Specifically, there is a lack of granularity on the contribution of the plastics lifecycle to total greenhouse gas (GHG) emissions and implications for the remaining global carbon budget for meeting international climate goals.[2] This is due to several issues. First, the emissions contribution of different production stages (see Figure 2) by plastic polymer type, from the extraction of fossil fuels through the shaping of the final plastic product, are poorly understood and communicated. Second, only a few analyses in recent literature attempt to estimate GHG emissions from the global plastics industry [3,5,17-22]. Systems boundaries in some of these studies are either too limited (from polymerization onward; see Figure 2) or the contribution of different production steps per plastic polymer type is incomplete or not communicated transparently. Third, the simplified representation of co-products and by-products in the production process and the lack of polymer-specific emission intensity values cause significant underestimation of GHG emissions from the plastics value chain. In addition, multiple processes are used to produce the same plastic polymer, with significant variations in process energy demand and yields. The type of process used depends on the production location and the availability and economics of required hydrocarbons. Thus, an average emission intensity that is indicative of plastic polymer production in a particular region will not be representative of other regions. For example, ethane-based steam cracking in the U.S. versus naphtha-based steam cracking in Europe will have very different emission intensity levels despite producing the same monomers (e.g., ethylene and propylene) and polymers (e.g., PE, PP, and PET). There is also a lack of detailed, transparent process and production data in some literature that masks which intermediate products are and are not included in the analysis. Consequently, methodological differences and a lack of transparency obscure the true climate impact of plastic production.

In addition to fossil-based feedstock, the plastics industry also consumes fossil fuels – oil, natural gas, and coal – for energy needed in production processes. The majority of processes used throughout plastic production (i.e., from the extraction of fossil fuels through the shaping of the final plastic product) are extremely energy- and GHG emission-intensive, requiring high operational temperatures and large amounts of power [8]. GHG emissions, primarily carbon

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[1] See UNEP/EA.5/Res.14. entitled "End plastic pollution: towards an international legally binding instrument" for more information.

[2] The remaining carbon budget (RCB) is the net amount of carbon dioxide (CO_2) humans can still emit while keeping global warming below a given limit with a given probability, taking into account the effect of other anthropogenic climate forcers [23].

dioxide (CO_2), are generated during the extraction, mining, and/or processing of fossil fuels needed for feedstock and fuel energy, and during plastic production through fossil fuel combustion for process heat and electricity use. In addition to energy-related emissions, some stages (e.g., crude oil and natural gas extraction) and some processes (e.g., steam and catalytic cracking of hydrocarbons) are associated with high amounts of process GHG emissions, including CO_2 and non-CO_2 emissions such as methane (CH_4), nitrous oxide (N_2O), and fluorinated gases.

Primary plastic production

| Extraction and/or mining (of fossil fuels) | Hydrocarbon refining and processing | Other chemicals production (non-hydrocarbon) | Monomer production | Polymerization | Product shaping |
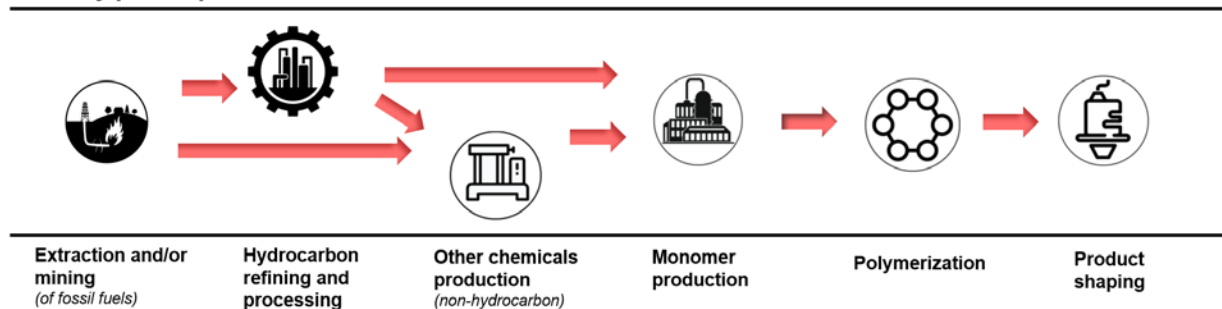
Figure 2. Production stages of the plastics value chain.

Notes: Polymerization or monomer production and polymerization are sometimes referred to as resin production.

The recent Intergovernmental Panel on Climate Change (IPCC) Assessment Report made it clear that without an immediate reduction of GHG emissions, the mean global temperature is likely to increase by more than 1.5°C above pre-industrial levels by 2050 with severe consequences across the planet [23]. Avoiding devastating climate change requires rapid actions in every sector on a global scale, including plastic production. This starts with a more granular understanding of GHG emissions from plastic polymer production.

This report presents an analysis that estimates the GHG emissions from primary plastic production and highlights its significant impact on climate change. It provides a science-based, technically neutral, and transparent foundation to inform negotiations on the development of a global plastic treaty and under the UNFCCC framework. We have developed comprehensive bottom-up modeling of GHG emissions from global primary plastic production, with a special focus on plastic polymer value chains, including all production stages (from extraction of fossil fuels to shaping of the final product), processes and technologies used in polymer production value chains. In addition to CO_2 emissions, our modeling also accounts for non-CO_2 emissions such as methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. Such detailed modeling of individual plastic polymers, where production value chain stages are fully considered, provides more granular and accurate estimates of GHG emissions from global primary plastic production. Such modeling is critical to informing the global plastics treaty since most mitigation strategies emphasized in the treaty process are either polymer-specific or would have different implications per polymer, and can further enable better coordination with other global treaties on climate change (e.g., UNFCCC).

We specifically focus on modeling nine key plastic polymers that are produced and consumed in large quantities: three types of polyethylene (PE) – low-density (LDPE), linear low-density

(LLDPE), and high-density (HDPE) – ; polypropylene (PP); polyethylene terephthalate (PET); polyvinyl chloride (PVC); polystyrene (PS) and other key styrene-based plastics such as styrene acrylonitrile (SAN) and acrylonitrile butadiene styrene (ABS), and polyurethane (PU) — which collectively account for almost 80% of the current plastic demand [3]. This study focuses only on primary plastics produced from fossil fuel-based feedstocks, and excludes bio-based and recycled plastic production.[3] Bio-based plastic and recycled plastic constitute 1% and 6.3% of total plastic production, respectively [3,24]. However, current investments in expanded primary plastic production facilities are consistent with historical growth trends [8].

The modelling and results provided in this study do not go beyond plastic production and do not evaluate GHG emission impact from the use and end-of-life stages. Previous research indicated that end-of-life management measures such as incineration and waste-to-energy would have additional climate impact [3,17,25]. Both of these practices also generate toxic air pollution that is harmful to human health due to the chemicals released [14], and could be particularly harmful to often-adjacent communities. In addition, significant further work is needed to advance our understanding of the GHG impact of plastics in "use" (e.g., some applications in the food and transportation sectors). We also do not evaluate the broader portfolio of clean technologies and their potential impact on future emissions; rather, we provide a picture of the magnitude of the climate problem related to plastic production under the assumption that the current production structure remains unchanged.

2. Methodology

This section defines the details of the bottom-up energy and emissions system modeling of the production processes and technologies used to produce various types of primary plastics in order to assess the climate impact of primary plastic production. Production of each plastic polymer type has been modeled separately. The modeling is a detailed system modelling of process and technology relations. It tracks the flows and production of input and output materials among processes and technologies. Every process technology is also defined with energy intensity of production and production-related GHG emissions.

The primary production of plastics has six key steps (Figure 3): (1) Extraction and/or mining, (2) hydrocarbon refining and processing, (3) other chemicals (non-hydrocarbon) production, (4) monomer production, (5) polymerization, and (6) product shaping. Each step has distinct characteristics, from the production equipment and technology type to fuel consumption and emissions. Almost all plastics are made from fossil fuel feedstocks, namely crude oil, natural gas, and coal. Extraction and/or mining step includes extraction, hydraulic fracturing, mining, and other processes involved in the extraction of fossil fuels. The fossil fuel feedstocks are then refined or processed into various hydrocarbons used for the production of monomers. Some hydrocarbons (e.g., heavy naphtha) are further processed to generate aromatics (i.e., benzene, toluene, and xylene, or "BTX") that are later used in production of some primary plastics. Some monomers also require other non-hydrocarbon chemicals (e.g., chlorine, formaldehyde, etc.) in their production. Next, monomers are chemically combined to create larger molecules called polymers via the polymerization process. Polymerization or polymerization and monomer production are sometimes referred to as resin production. Polymer pellets, flakes, powders and/or

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[3] In this study, "primary plastics" refers to the synthetic plastics in primary forms, also known as virgin plastics.

liquids are processed and shaped into finished products for various end-use applications (e.g., packaging, fibers, pipes, tubes, etc.) at the final stage.

This analysis focuses primarily on the energy consumption and GHG emissions associated with the production of primary plastics polymers. It does not include the production of additives to plastic polymer solutions that enhance the features of the final plastic products (e.g., Ultraviolet (UV) stabilizers, colors, etc.). We also do not model the production of catalysts that are used in some processes in small amounts. Additionally, when used alone in this report, "polymer" refers only to synthetic and fossil-fuel based primary plastic polymers and does not represent natural, semi-synthetic, or recycled polymers. Figure 3 shows all materials included in this analysis for the production of the nine plastic polymers discussed in this report.

Extraxtion and/or mining (of fossil fuels)	Hydrocarbon refining and processing	Other chemicals production (nonhydrocarbon)	Monomer production	Polymerization	Product shaping
• Coal • Crude oil • Natural gas	• Light Naphtha • Heavy Naphtha • Ethane • Propane • Butene • LPG • HCTO • VGO • P-xylene • Toluene • Pygas	• Methanol • Ammonia • Acetic acid • Chlorine • Nitric acid • Phosgene • Formaldehyde • Ethylene dichloride • Aniline • CO • Hydrogen peroxide	• Ethylene • Propylene • Butadiene • PTA • EG • VCM • Styrene • Acrylonitrile • MDI • TDI • Benzene • Ethylbenzene • EO, PO • LAO	• LDPE polymer • LLDPE polymer • HDPE polymer • PP polymer • PET polymer • PVC polymer • PS polymer • ABS polymer • SAN polymer • PU polymer • Polyol • Polybutadiene	• LDPE • LLDPE • HDPE • PP • PET • PVC • PS • SAN • ABS • PU

Figure 3. Production stages of primary plastics with material details.

Notes: A hydrocarbon is an organic compound consisting entirely of hydrogen and carbon. Ethylene dichloride (EDC) is a chlorinated hydrocarbon, in which chlorine substituted for hydrogen. Since EDC does not contain hydrogen and is not always a direct refinery output, it is considered under the "Other chemicals production" step in this analysis. Similarly, although benzene is a trimer, a chemical compound comprising three monomer units, it is considered under "Monomer production" in this analysis.

ABS = acrylonitrile butadiene styrene, CO = carbon monoxide, EG = ethylene glycol, EO = ethylene oxide, HCTO = hydrocracker tail oil, HDPE = high-density polyethylene, LAO = linear alpha olefins, LDPE = low-density polyethylene, LLDPE = linear low-density polyethylene, LPG = liquid petroleum gas, MDI = methylene diphenyl diisocyanate, PET = polyethylene terephthalate, PO = propylene oxide, Polyol = polyolefins, PP = polypropylene, PS = polystyrene, PTA = purified terephthalic acid, PU = polyurethane, PVC = polyvinyl chloride, P-xylene = paraxylene, Pygas = pyrolysis gasoline, SAN = styrene acrylonitrile, TDI = toluene diisocyanate, VCM = vinyl chloride monomer, VGO = vacuum gas oil.

Material flow analysis (MFA) has been used to study many different types of materials in the literature to track the flows and production of input and output materials in industrial production systems, including plastics [26-29]. Most early MFAs of plastics evaluated plastics as a single class of materials without distinguishing between individual polymers [30]. Several other studies addressed individual polymers including PE, PP, PET, PVC, PS, ABS, and PU [30-35]. However, most studies are dedicated to specific regions, production types or routes, and process

technologies. In addition, most processes used in the production value chain of primary plastics generate multiple products. In some MFA literature, some important products have been considered only as by-products of other production streams, such as the production of propylene and pyrolysis gasoline (pygas) during the steam cracking process targeting ethylene production, or the production of propylene or BTX along with gasoline in the fluid catalytic cracking (FCC) and catalytic reforming units of refineries [36-41]. In addition, some monomers (e.g., ethylene) are used in the production of multiple polymers, and some hydrocarbons (e.g., naphtha) are used in the production of multiple monomers.

The practice of allocating energy consumption and emissions to inputs and outputs across multiple product lines, known as "coproduct allocation," can be done based on different criteria. In the literature, multiple allocation methods are used for coproduct allocation: mass, stoichiometric, elemental, reaction enthalpy, and economic allocation [42]. The literature agrees that no single allocation method is superior. In this analysis, we track materials by mass and apply a *mass allocation criterion* when modeling material output from production systems with multi-output products. The ratio of the mass of the coproduct over the total mass output was used from the total outputs of the process. With this allocation, we can associate GHG emissions to the products based on production volume, not sale, energy content, or other characteristics.

In addition to fossil fuel feedstock, the primary plastics industry consumes fossil fuels for energy needed in production processes. Process energy is used to generate the heat, pressure, and electricity required for production.

The sources of GHG emissions from plastic production can be divided into direct emissions (i.e., emissions from production processes – (1) energy related emissions from combustion of fossil fuels for process heat and pressure, (2) non-energy related process emissions) and indirect emissions (i.e., electricity use). In addition to energy-related emissions, some stages (e.g., crude oil and natural gas extraction) and some processes (e.g., steam and catalytic cracking of hydrocarbons) are associated with high amounts of process GHG emissions, including CO_2 and non-CO_2 emissions, such as methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. In this analysis, GHG emissions across the plastics value chain are quantified as CO_2-equivalents (CO_2e) using 100-year Global Warming Potential (GWP-100) values from IPCC's Sixth Assessment Report (AR6) [23].

This study uses a combination of relevant literature data, process modeling, and validation by industry experts to generate its material flows and associated process energy consumption and GHG emissions results. Peer-reviewed studies are the first choice for data selection. Where data is unavailable (e.g., mass and energy intensity), as is the case for some processes, data is validated with inputs from industry experts and market research reports, and publicly available statistics. All data used in the modeling and analysis are transparently displayed in the main text or in the accompanying Supplementary Appendices.

In the below sub-sections, we present the overall production details, material flows, energy intensity, and emissions data related to production of for nine key plastic polymer types: LDPE, LLDPE, HDPE, PP, PET, PVC, PS, SAN&ABS, and PU. Section 3 then defines the basic processes and technologies used commonly in the production of primary plastics.

2.1. Polyethylene

PE is a thermoplastic polymer that is widely used in products from different market segments such as packaging, construction, electrical and electronic equipment, consumer products, and vehicle technical parts [43]. PE can be classified into several different types based on the structure of their molecular chains. More common types on the market are LDPE, LLDPE, and HDPE.

2.1.1. Low-Density Polyethylene

Figure 4 shows the production flow chart of LDPE, including input/output relationships and process technology details. Crude oil, natural gas, and coal are key feedstocks to refineries and processing units for conversion into hydrocarbon products such as light naphtha, ethane, LPG (liquid petroleum gas), VGO (vacuum gas oil), and HCTO (hydrocracking tail oil); while not represented in the figure, they are also energy inputs into process/technology units, alongside electricity. This is relevant for all plastic types, not just for LDPE. Globally, most ethylene is produced by the steam cracking of light naphtha and ethane (see Section 3.3 for details of ethylene production). LDPE, like all PE, is produced by the polymerization of ethylene.

Figure 4. LDPE production value chain and material flow chart.

Notes: ADU = atmospheric distillation unit, VDU = vacuum distillation unit, Gas mix = a mix of LPG, propane, and butene, LPG = liquid petroleum gas, AGO = atmospheric gas oil, VGO = vacuum gas oil, SMR = steam methane reformer, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, H2 = hydrogen, LDPE = low-density polyethylene.

- *Product shaping:* LDPE plastic products

LDPE products are generally shaped into finished products via four main manufacturing processes: blow molding, injection molding, film extrusion, and other types of extrusion (e.g., profile) (Figure 5). Film extrusion is the most common manufacturing process used to convert LDPE products, accounting for over 70% of global LDPE production. It also requires the least energy among product shaping processes. Section 3.1 provides more details on the production processes used to shape LDPE products, while Appendix Tables A.1 and A.2 contain the energy consumption data used in this analysis. We assume a production ratio of 1.01 tonnes polymer input per tonne of finished product to account for polymer loss during the conversion/shaping of plastic products. This is relevant for all plastic products included in this study.
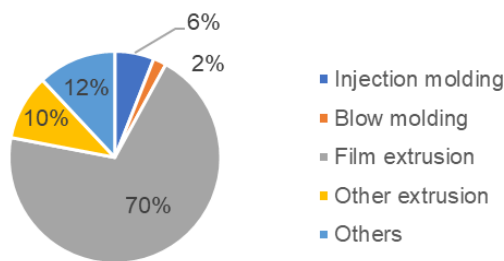
Figure 5. Share of different manufacturing processes used for LDPE products in this analysis.

Notes: "Others" could include processes such as rotational molding and other thermoforming methods.
Source: [44-46]

- *Polymerization:* LDPE polymer

The LDPE polymer is produced by the free-radical polymerization of ethylene at high temperatures (80-300°C) and high pressures (150-350 MPa) [47].[1] Free-radical polymerization is a type of chain-growth polymerization in which the polymer is formed by successive additions of building blocks to a propagating radical chain; this can occur under bulk, solution, emulsion, suspension (slurry), and high temperature/pressure conditions [48]. Polymerization requires a high amount of electric power, and the energy intensity of this process ranges from 2.9 to 9 gigajoule (GJ) per tonne of LDPE in the literature [49-55]. This wide range could be attributed to the reactor type (i.e., tubular vs autoclave) and varying levels of technology efficiency in the market, as well as desired polymer characteristics (e.g., strength, flexibility, etc.). Section 3.2 provides more details on the process used for free-radical polymerization, while Appendix Tables A.3 and A.4 contain the energy consumption data used in this analysis.

In this study, we assume that the unit energy consumption of LDPE polymerization is 5.2 GJ per tonne. We also assume a production ratio of 1.02 kg ethylene per kg LDPE polymer, based on Russo et al. [49] and EC [56].

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[1] MPa stands for "MegaPascal".

- *Monomer production: Ethylene*

Ethylene is the only monomer used for LDPE production. Please see Section 3.3 for details about ethylene production processes (i.e., steam cracking and MTO).

- *Hydrocarbon production: Light naphtha, ethane, "gas mix", VGO, and HCTO*

Light naphtha, ethane, gas mix (of LPG, propane, and butane, henceforth called "gas mix"), VGO, and HCTO are the hydrocarbons used in the steam cracking of ethylene.[2] Please see Section 3.4 for production details.

- *Other chemical compounds production: Methanol*

Methanol is used in the MTO process to synthesize ethylene. Please see Section 3.5.1 for details of methanol production processes, based on different feedstocks.

- *Extraction and/or mining of fossil fuels: Crude oil, natural gas, and coal*

Modeling of GHG emissions related to the extraction, fracking, and mining of crude oil, natural gas, and coal for the feedstock and fuel energy needs of LDPE plastic production is defined in Section 3.6.

2.1.2. Linear Low-Density Polyethylene

LLDPE is a substantially linear polymer of PE, with significant numbers of short branches, and is commonly made by the copolymerization of ethylene with longer-chain alpha-olefins [43]. Figure 6 shows the production flow chart of LLDPE with input/output products and process technology details. The hydrocarbons and methanol are used as input materials to produce the monomer ethylene and the comonomer "linear alpha-olefin" (LAO), which is later converted to the LLDPE polymer via the polymerization process.

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[2] LPG is also a mix of propane and butene.
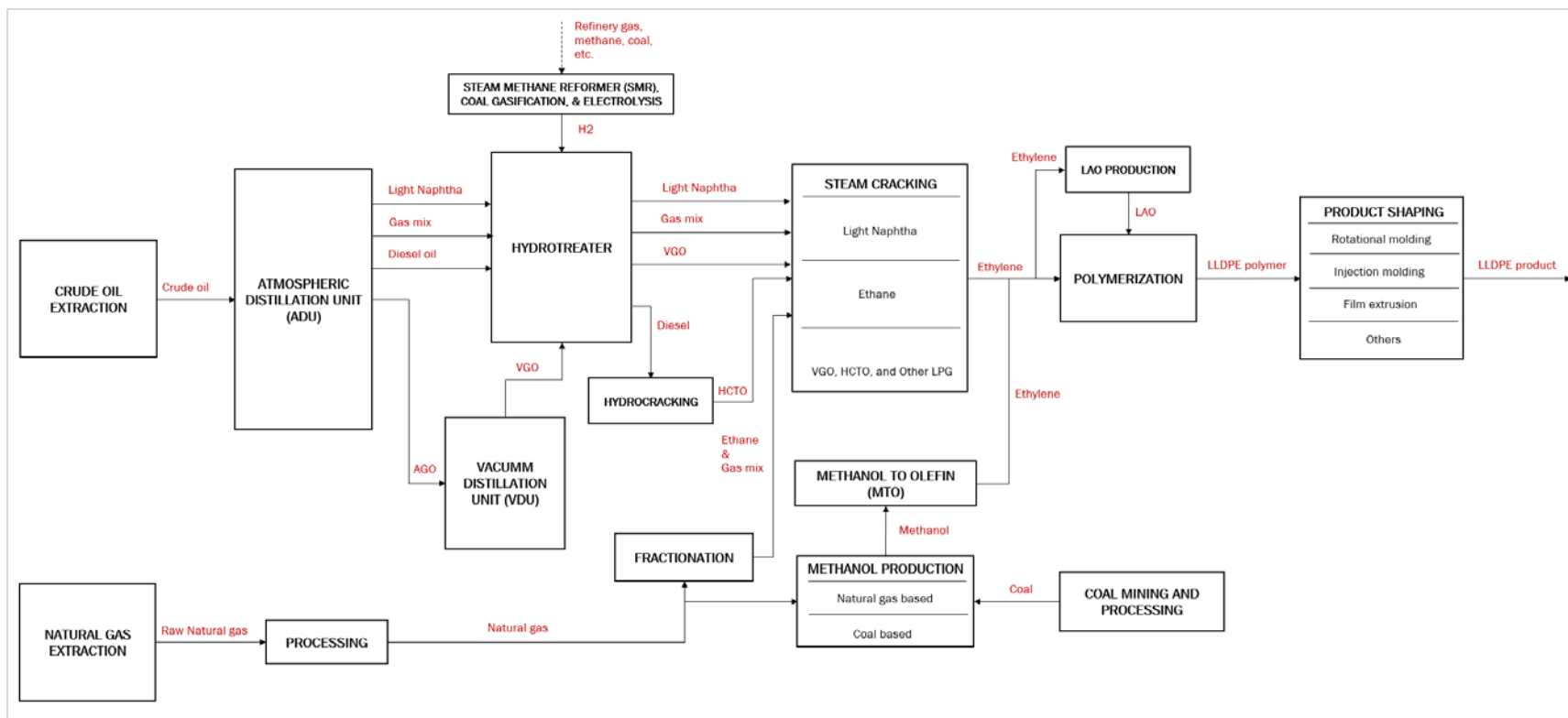
Figure 6. LLDPE production value chain and material flow chart.

Notes: ADU = atmospheric distillation unit, VDU = vacuum distillation unit, Gas mix = a mix of LPG, propane, and butene, LPG = liquid petroleum gas, AGO = atmospheric gas oil, VGO = vacuum gas oil, SMR = steam methane reformer, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, LAO = linear alpha-olefins, H2 = hydrogen, LLDPE = linear low-density polyethylene.

- *Product shaping:* LLDPE products

LLDPE is generally shaped into final products via film extrusion and molding (Figure 7). As in LDPE, film extrusion is the most common manufacturing type, accounting for 70% of global LLDPE production. Section 3.1 provides more details on the production process used to shape LLDPE products, while Appendix Tables A.1 and A.2 contain energy consumption data used in this analysis.
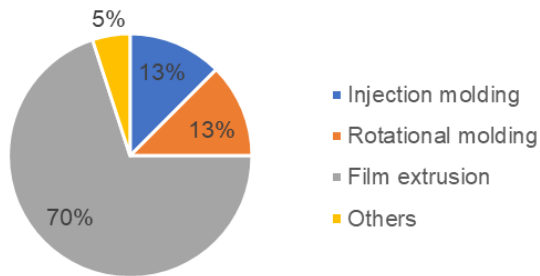
Figure 7. Share of different manufacturing processes used for LLDPE products in this analysis.

Notes: "Others" could include processes such as blow molding, other types of extrusion, and mixing. Source: [44-46, 57,58]

- *Polymerization:* LLDPE polymers

LLDPE is a linear PE produced in a low-pressure process. It is manufactured via the copolymerization of ethylene and LAO comonomers [59,60]. Concentration of the LAO comonomer in the polymerization process changes the density of the resin [56]. While the concentration of comonomers incorporated in LLDPE can be as low as 3%, the global average is between 8% and 10% [61,62]. In our analysis, we assume comonomers' share in LLDPE production is 9%, based on calibration data in 2019.[1]

Three main low-pressure technologies are used in LLDPE polymerization: solution, gas-stage, and suspension (slurry) processes [64]. Globally, 21% and 75% of LLDPE is produced via solution and gas-stage processes, respectively [65]. The rest (4%) is from the slurry process. Section 3.2 provides more details on these polymerization processes. According to the literature, the energy intensity of the solution and suspension processes ranges between 2.7 and 3 GJ per tonne of LLDPE, while the gas-stage process has a higher energy consumption range of 3.8 to 4.1 GJ per tonne [49-51]. In this study, for LLDPE polymerization, we assume a weighted-average unit energy consumption of 3.3 GJ per tonne of LLDPE. We also assume a production ratio of 1.02 tonnes of ethylene per tonne of LLDPE polymer, based on Russo et al. [49] and EC [56]. Appendix Tables A.3 and A.4 contain the energy consumption data used per polymer type for polymerization.

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[1] In 2020, global production of linear alpha olefins (LAOs) was estimated at around 5.76 Mt, of which about 65% was used for PE comonomers [63].

- *Monomer production: Ethylene and LAOs*

Ethylene is the main monomer used for LLDPE production, along with the comonomers LAOs. Ethylene is also the preferred input material in the production of LAOs. LAOs are also used for HDPE production, but in lesser amounts. Please see Section 3.3 for details about the ethylene and LAO production processes.

- *Hydrocarbon production: Light naphtha, ethane, "gas mix", VGO, and HCTO*

Light naphtha, ethane, gas mix, VGO, and HCTO are the hydrocarbons used in the steam cracking of ethylene. Please see Section 3.4 for details about the production of light hydrocarbons used in the steam cracking of ethylene.

- *Other chemical compounds production: Methanol*

Methanol is used in the MTO process to synthesize ethylene. Please see Section 3.5.1 for details about methanol production processes using different feedstock.

- *Extraction and/or mining of fossil fuels: Crude oil, natural gas, and coal*

Modeling of GHG emissions related to the extraction, fracking, and mining of crude oil, natural gas, and coal for the feedstock and fuel energy needs of LLDPE plastic production is defined in Section 3.6.

2.1.3. High-Density Polyethylene

HDPE is produced in low-pressure reactors and has a very linear structure with few short chain branches [66]. Similar to LLDPE, LAOs are used as comonomers in the production, but to a lesser degree [61]. HDPE plastic is used in a wide variety of applications, including plastic bottles, milk jugs, shampoo bottles, bleach bottles, cutting boards, and piping. Figure 8 shows the production flow chart of HDPE with input/output products and process technology details. Hydrocarbons and methanol are used as input materials to produce the monomer ethylene and comonomer LAO, which is later converted to the HDPE polymer via the polymerization process.

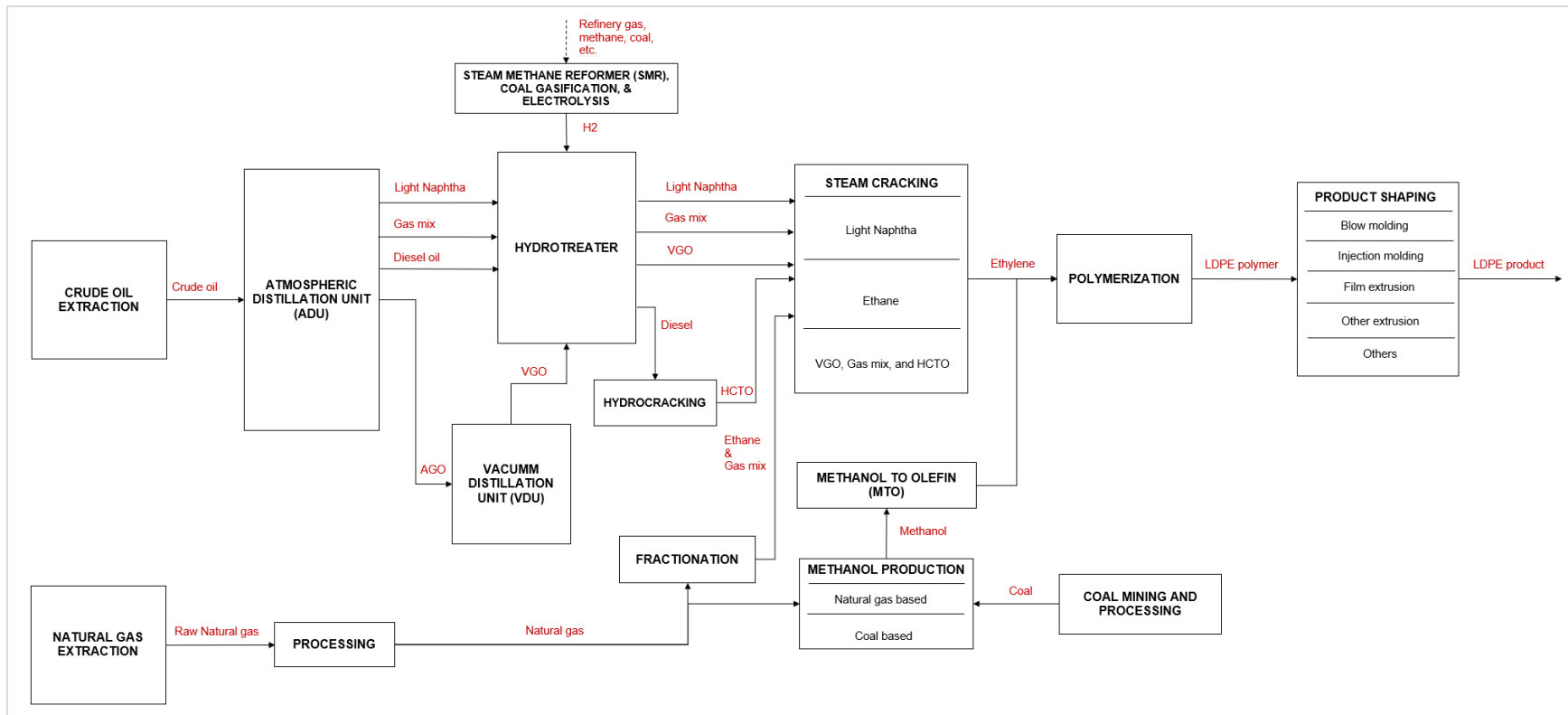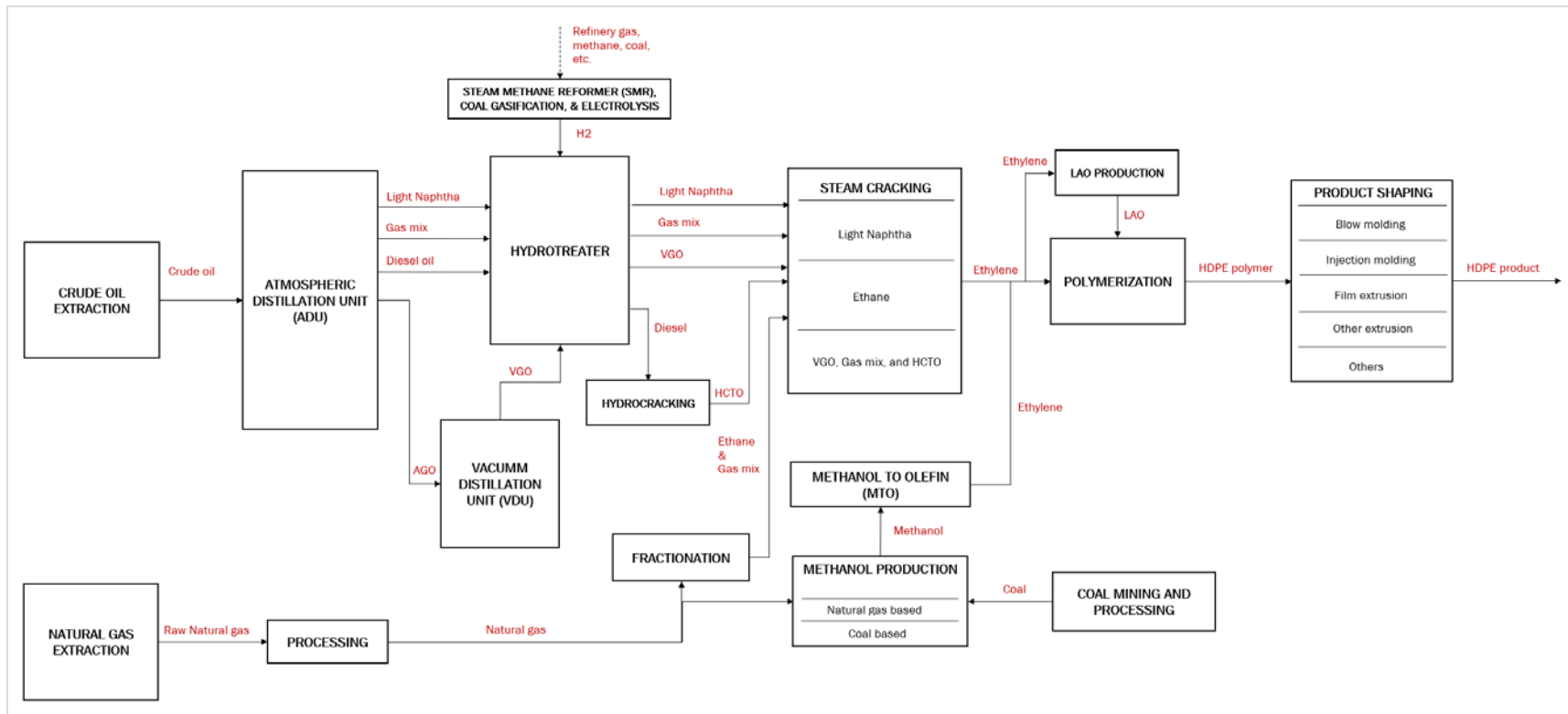*Figure 8. HDPE production value chain and material flow chart.*

Notes: ADU = atmospheric distillation unit, VDU = vacuum distillation unit, Gas mix = a mix of LPG, propane, and butene, LPG = liquid petroleum gas, AGO = atmospheric gas oil, VGO = vacuum gas oil, SMR = steam methane reformer, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, LAO = linear alpha-olefins, H2 = hydrogen, HDPE = high-density polyethylene.

- *Product shaping: HDPE products*

The most important technologies used for processing HDPE pellets into finished products are extrusion, injection, and blow molding, with extrusion being the most common (Figure 9). Film extrusion and blow molding accounted for 28% and 25% of global HDPE production in 2019, respectively. Section 3.1 provides more details on the production process used to shape HDPE products, while Appendix Tables A.1 and A.2 contain the energy consumption data used in this analysis.
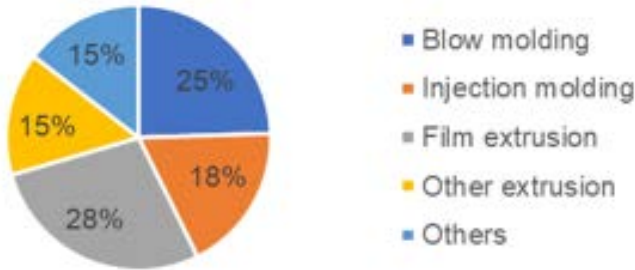
Figure 9. Share of different manufacturing processes used for HDPE products in this analysis.

Notes: "Other extrusion" could include profile and sheet extrusion. "Others" could include compression molding. Source: [45,46,67,68]

- *Polymerization: HDPE polymer*

HDPE is produced using similar processes to LLDPE, namely solution, gas-stage, and suspension (slurry) processes [61]. Both are manufactured via the copolymerization of ethylene and a LAO comonomer at low pressure based on different catalyst systems [59,60]. The average level of comonomer content used in HDPE production is between 0.5% and 3% [61]. In our analysis, it is assumed that comonomers' share in HDPE production is 1.5%, based on calibration data in 2019.[1]

Globally, 60% and 25% of HDPE are produced via solution and gas-stage processes, respectively [65]. The rest (10%) is from the slurry process. Section 3.2 provides more detail on these polymerization processes. According to the literature, the energy intensity of the solution, gas-stage, and suspension processes ranges between 2.3 and 5.4 GJ per tonne of HDPE [49,51-56]. In this study, we assume the weighted average unit energy consumption of HDPE polymerization is 3.25 GJ per tonne HDPE. We also assume a production ratio of 1.03 kg ethylene per kg HDPE polymer based on Russo et al. [49], EC [56] and Rangel [69]. Appendix Tables A.3 and A.4 contain the energy consumption data used per polymer type for polymerization.

- *Monomer production: Ethylene, LAOs*

Ethylene is the main monomer used for HDPE production, along with the comonomers LAOs. Ethylene is also the preferred input material in the production of LAOs. Please see Section 3.3 for details about the ethylene and LAO production processes.

- *Hydrocarbon production: Light naphtha, ethane, "gas mix", VGO, HCTO*

Light naphtha, ethane, gas mix, VGO, and HCTO are the hydrocarbons used in the steam cracking of ethylene. Please see Section 3.4 for details about the production of light hydrocarbons used in the steam cracking of ethylene.

- *Other chemical compounds production: Methanol*

Methanol is used in the MTO process to synthesize ethylene. Please see Section 3.5.1 for details about methanol production processes using different feedstock.

- *Extraction and/or mining of fossil fuels: Crude oil, natural gas, and coal*

Modeling of GHG emissions related to the extraction, fracking, and mining of crude oil, natural gas, and coal for the feedstock and fuel energy needs of HDPE plastic production is defined in Section 3.6.

2.2. Polypropylene

PP is used in numerous applications across different market segments including household items, automotive components, packaging, textiles, and others [56,70]. Figure 10 shows the production flow chart of PP, with input/output relationships and process technology details. PP is produced by the polymerization of propylene. Globally, most propylene is produced by the steam cracking of hydrocarbons and by fluid catalytic cracking (FCC) units in petroleum refineries. Propylene can also be produced via new processes such as propane dehydrogenation (PDH), MTO, or methanol to propylene (MTP), and other processes such as Metathesis and Superflex see Section 3.3 for details).
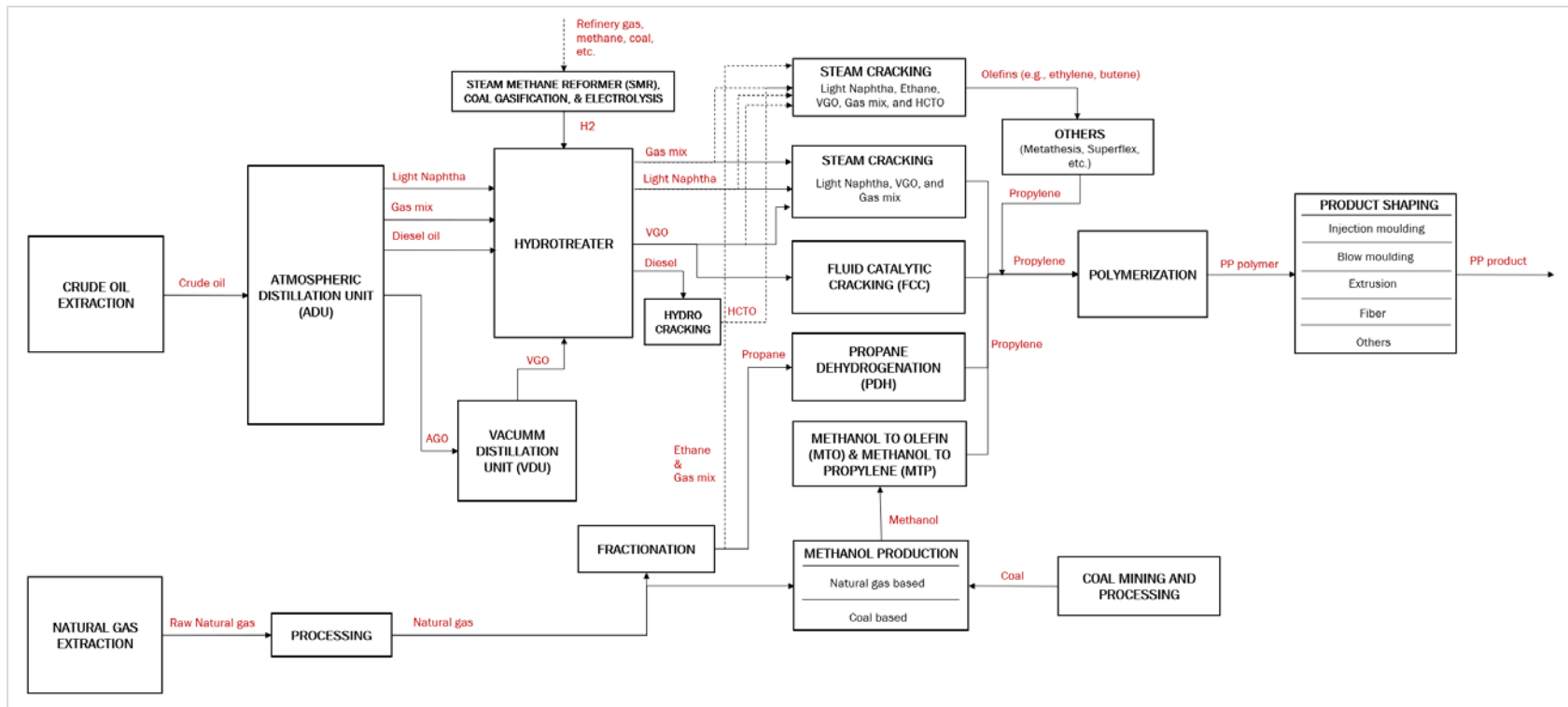
Figure 10. PP production value chain and material flow chart.

Notes: ADU = atmospheric distillation unit, VDU = vacuum distillation unit, Gas mix = a mix of LPG, propane, and butene, LPG = liquid petroleum gas, AGO = atmospheric gas oil, VGO = vacuum gas oil, SMR = steam methane reformer, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, MTP = methanol-to-propylene, FCC = fluid catalytic cracking, PDH = propane dehydrogenation, H2 = hydrogen, PP = polypropylene.

- *Product shaping:* PP products

PP products are generally shaped into finished products via four processing types: blow molding, injection molding, extrusion, and fiber production (Figure 11). Injection molding is the most common process used to convert PP products, accounting for almost 40% of global PP production. Section 3.1 provides more details on the production process used to shape plastic products, while Appendix Tables A.1 and A.2 contain the energy consumption data used in this analysis.
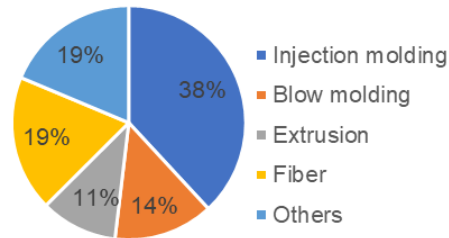
Figure 11. Share of different manufacturing processes used for PP products in this analysis.

Notes: Fiber production is mostly based on monofilament extrusion.
Source: [45,46,71-73].

- *Polymerization:* PP polymer

The polymerization of PP is similar to PE, in that the propylene monomer is subjected to heat and pressure in the presence of a catalyst system. Polymerization is achieved at a relatively low temperature (60-80°C) and low pressure (3-4 Mpa) [74]. Five processes commonly used for PP polymerization are solution, suspension (slurry), gas stage, bulk (or liquid PP), and hybrid (bulk plus gas stage) polymerization [59]. According to recent literature, the energy intensity of PP polymerization processes ranges between 2.4 and 4.9 GJ per tonne of PP [51,53,75,76]. In this study, for PP polymerization, we assume an average unit energy consumption of 3.7 GJ per tonne PP. We also assume a production ratio of 1.02 tonnes ethylene per tonne PP polymer based on Russo et al. [49]. Appendix Tables A.3 and A.4 contain the energy consumption data used per polymer type for polymerization.

- *Monomer production:* Propylene

In most production routes, propylene is the main monomer used for PP production. However, new production processes can also require other monomers. For example, Metathesis and Superflex require a mixture of ethylene and butene comonomers to convert to propylene. Please see Section 3.3 for details about propylene production processes, steam cracking, FCC, MTO/MTP, PDH, and others.

- *Hydrocarbon production: Light naphtha, ethane, "gas mix", VGO, HCTO*

Light naphtha, ethane, gas mix (and separately, propane), VGO, and HCTO are the hydrocarbons used in the production of propylene. See Section 3.4 for details about different propylene production technologies.

- *Other chemical compounds production: Methanol*

Methanol is used in MTO and MTP processes to synthesize propylene. See Section 3.5.1 for details about methanol production processes using different feedstock.

- *Extraction and/or mining of fossil fuels: Crude oil, natural gas, and coal*

Modeling of GHG emissions related to the extraction, fracking, and mining of crude oil, natural gas, and coal for the feedstock and fuel energy needs of PP plastic production is defined in Section 3.6.

2.3. Polyethylene Terephthalate

PET is the most common plastic of the polyester family and is used in fibers. Figure 12 shows flow chart of PET with input/output products and process technology details. PET is a condensation polymer produced by the esterification of ethylene glycol (EG) with purified terephthalic acid (PTA) or dimethyl terephthalate (DMT) [55]. Globally almost all PET (>98 %) is produced from PTA [55]. Therefore, in this report, we focus on PTA based PET production. The monomers of PET, PTA and EG, are polymerized in the liquid stage to produce amorphous PET. This form of the polymer is suitable for the production of fibers and film [77]. Most bottle-grade PET is slightly modified through the addition of small amounts of an appropriate comonomer, such as isophthalic acid, during polymerization [78].
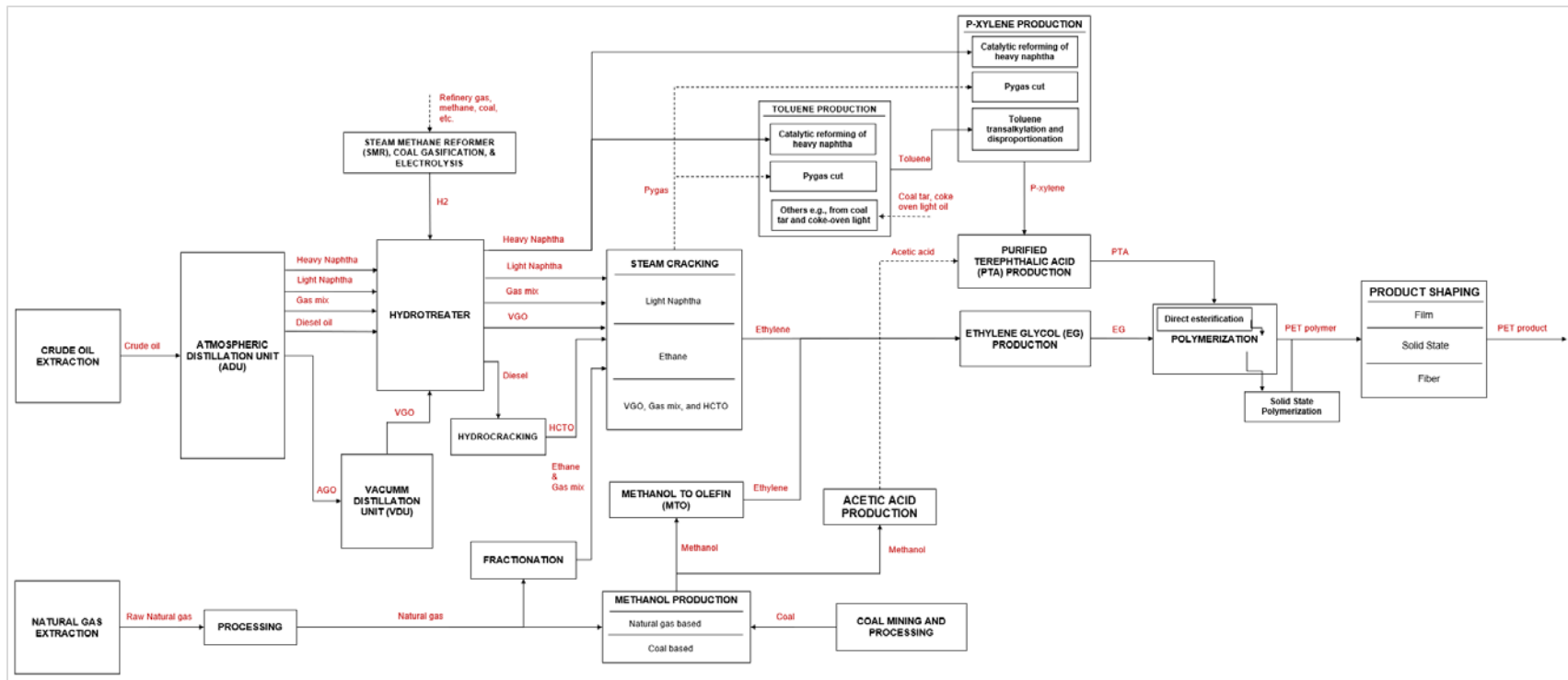
Figure 12. PET production value chain and material flow chart.

Notes: ADU = atmospheric distillation unit, VDU = vacuum distillation unit, Gas mix = a mix of LPG, propane, and butene, LPG = liquid petroleum gas, AGO = atmospheric gas oil, VGO = vacuum gas oil, SMR = steam methane reformer, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, H2 = hydrogen, Pygas = pyrolysis gasoline, EG = ethylene glycol, PTA = purified terephthalic acid, PET = Polyethylene terephthalate.

- *Product Shaping:* PET products

PET products are generally shaped into final products via blow molding, injection molding, extrusion, and fiber production (Figure 13). 67% of PET production in 2019 was for fibers. Section 3.1 provides more details on the production process used to shape fibers and films. The polymer pellets from solid state polymerization go through blow molding, injection molding, or extrusion processes to be shaped. Appendix Tables A.1 and A.2 provide the energy consumption data used in this analysis.
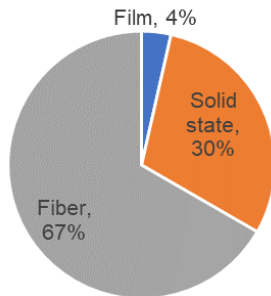
Figure 13. Share of different manufacturing processes assumed for PET products in this analysis. Source: [3,44,69]

- *Polymerization:* PET polymer

The polymerization reaction is operated under pressures of 2.7-5.3 kiloPascal (kPa) and at 270° to 290°C for stable (low-viscosity) PET, and 1.3-2.7 kPa and 280° to 300°C for industrial filament PET [79]. When very high molecular weights are desired, as is the case for bottle-grade PET resins, the polymerization may be carried out in an additional stage: solid-state polymerization (SSP). Solid-state polymerization of PET is carried out by heating the low molecular weight prepolymer at temperatures below its melting point but above its glass transition temperature [80]. SSP is a key step that is frequently used after melt-polymerization for the purpose of enhancing the mechanical and rheological properties of polymers before injection and blow molding or extruding.

The energy intensity of the PET polymerization process is around 3.5 GJ per tonne [49]. SSP can add an additional energy consumption of 0.2-0.5 GJ per tonne PET [81]. Based on this, in this study, we assume the unit energy consumption of PET polymerization is 3.5 GJ/tonne, plus 0.4 GJ/tonne of additional energy for the products that require SPP (which is ~30% of total PET production). We also assume a production ratio of 0.85 kg PTA and 0.35 kg EG per kg PET polymer during the production based on Russo et al. [49]. Appendix Tables A.3 and A.4 contain the energy consumption data used per polymer type for polymerization.

- *Monomer production:* PTA, EG, ethylene

Purified Terephthalic Acid:
PTA is one of the main monomers used for PET plastic production. PTA is produced by the catalytic liquid stage oxidation of p-xylene in acetic acid, in the presence of air [79]. The acetic

acid recovery system is one of the most energy-consuming units in the PTA production process [82]. The energy intensity of PTA plants is estimated to range from 5.3 to 9.7 GJ per tonne PTA [51,82,83]. In this study, we assume that average unit energy consumption of PTA production is 7.4 GJ per tonne PTA. About 0.8 kg p-xylene is used to produce a tonne of PTA [49,84].

Ethylene glycol:
EG is produced through a highly energy-intensive, two-step process in integrated chemical plants that are operated under high temperatures and pressures [85]. In this process, ethylene is first oxidized by oxygen on a silver-based catalyst to form ethylene oxide, followed by a hydrolysis reaction of ethylene oxide to ethylene glycol catalyzed by strong acid. The overall product yield is below 65% for this process due to the inevitable overoxidation of ethylene in the first step [49,85]. The energy consumption of the process ranges between 5.9 and 6.1 GJ per tonne [49,51]. We assume that 0.6 kg ethylene is used to produce a tonne of EG [49] and that the energy consumption is 6 GJ per tonne EG.

Ethylene:
See Section 3.3 for details about ethylene production processes, i.e., steam cracking and MTO.

- *Hydrocarbon production: Naphtha, ethane, "gas mix", VGO, HCTO, pyrolysis gasoline, p-xylene, toluene*

Naphtha (both light and heavy), ethane, gas mix, VGO, HCTO, pyrolysis gasoline (pygas), p-xylene, and toluene are the hydrocarbons used in the production of PET.

- *Other chemical compounds production: Acetic acid and methanol*

Acetic acid:
Acetic acid is a chemical reagent used primarily in the production of PTA. In the literature, the acetic acid to PTA ratio ranges between 0.04 and 0.09 tonne acetic acid per tonne PTA [86-88]. Based on market calibration, we assume that about 0.05 tonne of acetic acid is required to produce 1 tonne of PTA.[1]

Almost 75% of acetic acid production is from the carbonylation of the methanol process [93]. According to the literature, the feed molar ratio of acetic acid to methanol varies from 1:1 to 1:4 in the carbonylation of the methanol process [94]. In this study, we assume the ratio is 1:2, i.e., 2 tonnes of methanol are required to produce 1 tonne of acetic acid. The process consumes about 2.2 GJ energy per tonne acetic acid [93].

Methanol:
Methanol is used for acetic acid and ethylene production (from MTO). See Section 3.5.1 for details about methanol production processes using different feedstocks.

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[1] Total acetic acid production was 16.3 Mt in 2019 [89]. According to statistics, about 20% of this was used for PTA production [90-92].

- *Extraction and/or mining of fossil fuels: Crude oil, natural gas, and coal*

Modeling of GHG emissions related to the extraction, fracking, and mining of crude oil, natural gas, and coal for the feedstock and fuel energy needs of PET plastic production is defined in Section 3.6.

2.4. Polyvinyl chloride

PVC can be found in an extremely wide range of applications, such as construction products like window frames, pipes, and facade elements, or as products for mechanical or electrical engineering like cable insulation. PVC also has applications in food packaging and consumer goods.

Figure 14 shows the production flow chart of PVC with input/output relations and process technology details. PVC is manufactured by the polymerization of vinyl chloride monomer (VCM). The hydrocarbons are used as input feedstocks to produce monomer ethylene, which is later converted to ethylene dichloride (EDC) in a chemical reaction with chlorine. EDC is then used to produce VCM.
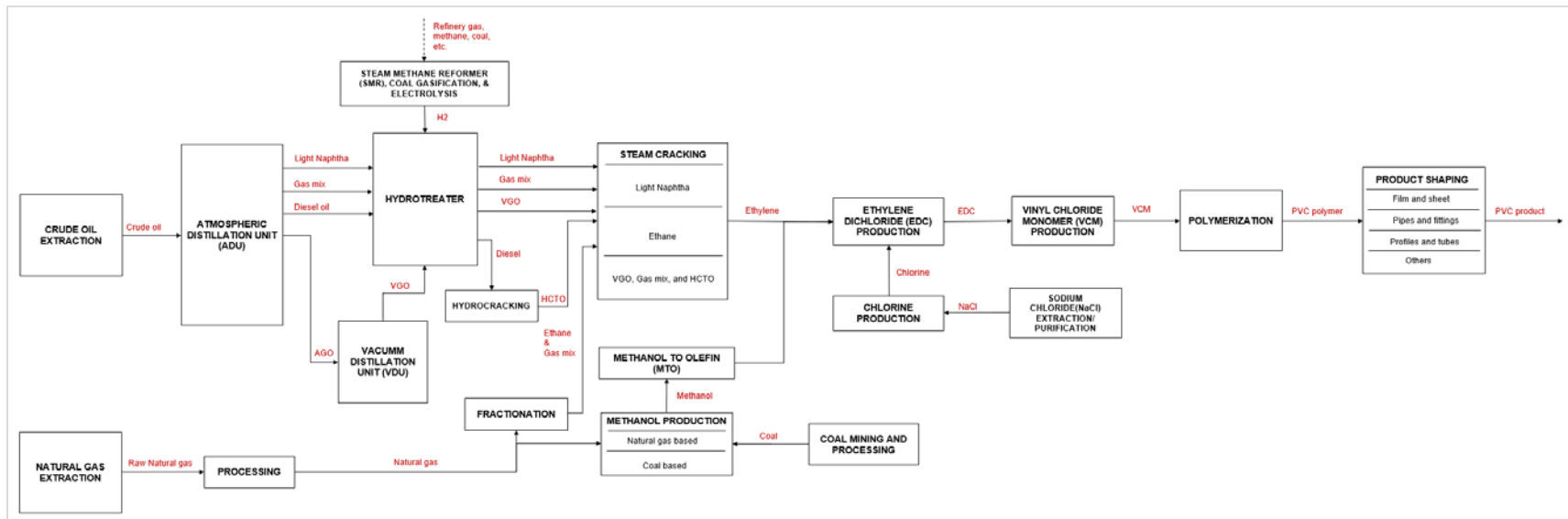
Figure 14. PVC production value chain and material flow chart.

Notes: ADU = atmospheric distillation unit, VDU = vacuum distillation unit, Gas mix = a mix of LPG, propane, and butene, LPG = liquid petroleum gas, AGO = atmospheric gas oil, VGO = vacuum gas oil, SMR = steam methane reformer, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, H2 = hydrogen, EDC = ethylene dichloride, VCM = vinyl chloride monomer, NaCl = sodium chloride, PVC = Polyvinyl chloride.

- *Product Shaping:* PVC products

PVC is widely used in construction, civil engineering material, and many consumer products. The majority of PVC resin is processed for the pipe, fittings, profiles, and tubing markets. Pipes and fittings products accounted for 45% of global PVC production in 2019 (Figure 15). Most pipes and tubes are manufactured by extrusion of raw material PVC resin. Fittings are a product of injection molding. See Appendix Tables A.1 and A.2 for the energy consumption data used in this analysis.
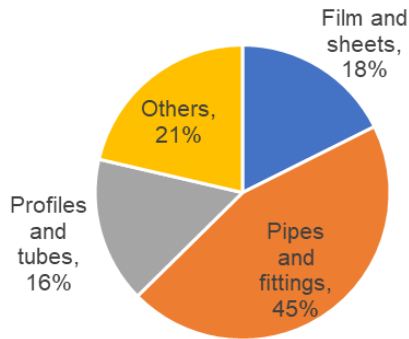
Figure 15. Share of of different types used for PVC products in this analysis.
Source: [95-97]

- *Polymerization:* PVC polymer

PVC is manufactured by the polymerization of VCM [49,56]. Pressure in the reactor usually ranges from 0.4 to 1.2 Mpa and the reaction temperature is between 35-70°C [98]. During the polymerization reaction, as little as 65% of the VCM is converted into PVC [49]. Other literature gives a range of an 85-97% conversion rate [98]. In this analysis, we assume a conversation rate of 92% (i.e., 1.1 kg VCM per kg PVC polymer).

Three processes are commonly used for the production of PVC: (1) suspension polymerization, (2) emulsion polymerization, and (3) bulk polymerization [53]. See Section 3.2 for a technical description of the polymerization processes. Suspension PVC is used for most rigid PVC applications such as pipes, profiles, building materials, and hard foils. It is also plasticized and used for most flexible applications such as cable insulation, soft foils, and medical products [59]. Emulsion PVC is primarily used for coating applications such as PVC-coated fabrics. Bulk PVC is used for specific types of hard sheets and bottles. Suspension PVC accounts for more than 80% of PVC production [98,99]. The production share of emulsion and bulk PVC is approximately 10% and 5%, respectively. Appendix Tables A.3 and A.4 contain the energy consumption data used in this analysis.

CFC (Chlorofluorocarbon)-11 is released during VCM polymerization [98]. This potent gas causes ozone depletion and has climate change impacts. Based on Plastics Europe [98], we assume that 0.008 and 0.005 kg CO_2e/tonne PVC polymer are emitted from suspension and emulsion polymerization processes, respectively.

- *Monomer production: VCM, ethylene*

Vinyl chloride monomer:
The most common method of VCM production, accounting for over 95% of worldwide production, is by thermal cracking of EDC [49,100]. In this process, EDC is synthesized by the reaction of chlorine with ethylene over a catalyst. EDC is then thermally cracked at 425-550°C to produce VCM and hydrogen chloride. [101]. Hydrogen chloride can be recovered and recycled into the cracking process via reaction with oxygen and ethylene over a copper catalyst to make more EDC. The energy consumption of the process in the literature ranges between 2.5 and 7.5 GJ per tonne VCM [49,102]. For this study, we assume that energy consumption is 5 GJ per tonne VCM, with an additional energy consumption of 5 GJ per tonne EDC. Refer to Appendix Table A.5 for fuel consumption details.

In addition, 0.5 kg ethylene/kg EDC and 0.6 kg chlorine/kg EDC are used during the production of EDC, based on Russo et al. [49] and Pascault et al. [102]. Similar to PVC production, CFC-11 is also released during VCM production [98]. Based on Plastics Europe [98], we assume that 0.007 kg CO_2e per tonne VCM is emitted during VCM production.

In addition, exposure to VCM is toxic and a well-established animal and human carcinogen [103].

Ethylene:
See Section 3.3 for details about ethylene production processes, i.e., steam cracking and MTO.

- *Hydrocarbon production: Light naphtha, ethane, "gas mix", VGO, and HCTO*

Light naphtha, ethane, gas mix, VGO, and HCTO are the hydrocarbons used in the production of PVC. See Section 3.4 for details about the production of these hydrocarbons.

- *Other chemical compounds production: Chlorine, methanol*

Chlorine:
Chlorine is the key non-hydrocarbon chemical used for EDC production, along with ethylene. Total global production of chlorine reached over 84 million tons in 2019 [104]. Chlorine and its co-product, caustic soda (sodium hydroxide), are manufactured in electrochemical cells and are among the most energy-intensive industrial operations [105]. Commercially, three main production technologies are to produce chlorine [106]:
- Membrane technology, which represented more than half (59%) of global production in 2018;
- Mercury process, which accounted for 29%;
- And diaphragm process, which accounted for about 12%.

Table 2 summarizes the energy consumption of the chlorine production processes from the literature, along with our assumptions.

Table 2. Chlorine production energy consumption by production type

	Literature range	This study
Membrane	9.3-10 GJ/tonne chlorine	
Mercury	12.8-13.3 GJ/tonne chlorine	
Diaphragm	9.7-17 GJ/tonne chlorine	
Average	9.3-12.8 GJ/tonne chlorine	11.1 GJ/tonne chlorine

Source: [49,54,104,107,108]

Methanol:
Methanol is used for ethylene production (from MTO). See Section 3.5.1 for details about methanol production processes using different feedstocks.

- *Extraction and/or mining of fossil fuels: Crude oil, natural gas, and coal*

Modeling of GHG emissions related to the extraction, fracking, and mining of crude oil, natural gas, and coal for the feedstock and fuel energy needs of PVC plastic production is defined in Section 3.6.

2.5. Polystyrene, Styrene Acrylonitrile, and Acrylonitrile Butadiene Styrene

PS is an amorphous thermoplastic made from the monomer styrene [109].[1] PS can be classified into several different types. The common forms of PS are general purpose polystyrene (GPPS), high impact polystyrene (HIPS), expanded polystyrene (EPS), and extruded polystyrene (XPS) [110]. GPPS and HIPS are rigid PS plastics, while EPS and XPS are foams. GPPS and HIPS are used in many applications such as food and non-food packaging, disposable cups and cutlery, furniture, toys, and consumer goods, as well as electronics and appliances [98]. The major applications of EPS and XPS foams are in the construction industry, as thermal insulation for walls, cavities, roofs, floors, cellars and foundations, and lightweight packaging.

Figures 16 and 17 show the production of PS with input/output relations and process technology details. PS is produced by polymerization of a styrene monomer. While SAN and ABS are not considered PS polymers, they are common thermoplastic polymers that are also based on a styrene monomer. SAN is a co-polymer plastic consisting of styrene and acrylonitrile in the polymer chain. ABS is made of three monomers: acrylonitrile, butadiene, and styrene.

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[1] Amorphous polymers don't have a melting point — they have a glass transition temperature, or Tg {99}.
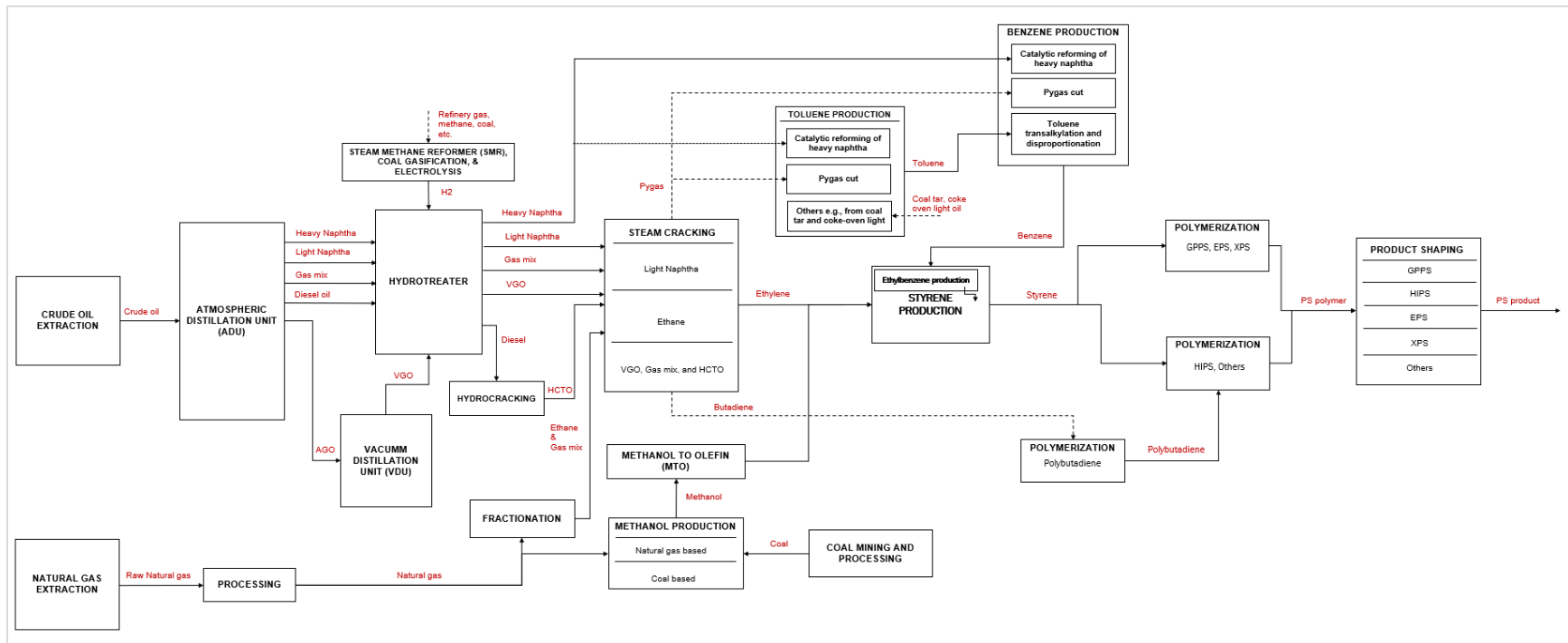
Figure 16. PS production value chain and material flow chart.

Notes: ADU = atmospheric distillation unit, VDU = vacuum distillation unit, Gas mix = a mix of LPG, propane, and butene, LPG = liquid petroleum gas, AGO = atmospheric gas oil, VGO = vacuum gas oil, SMR = steam methane reformer, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, H2 = hydrogen, GPPS = general purpose polystyrene, HIPS = high impact polystyrene, EPS = expanded polystyrene, XPS = extruded polystyrene, PS = polystyrene. Please note that expansion gases such as pentane, HCFC, and HFC that are used in the production of EPS and XPS in very small amounts are not presented in the chart.
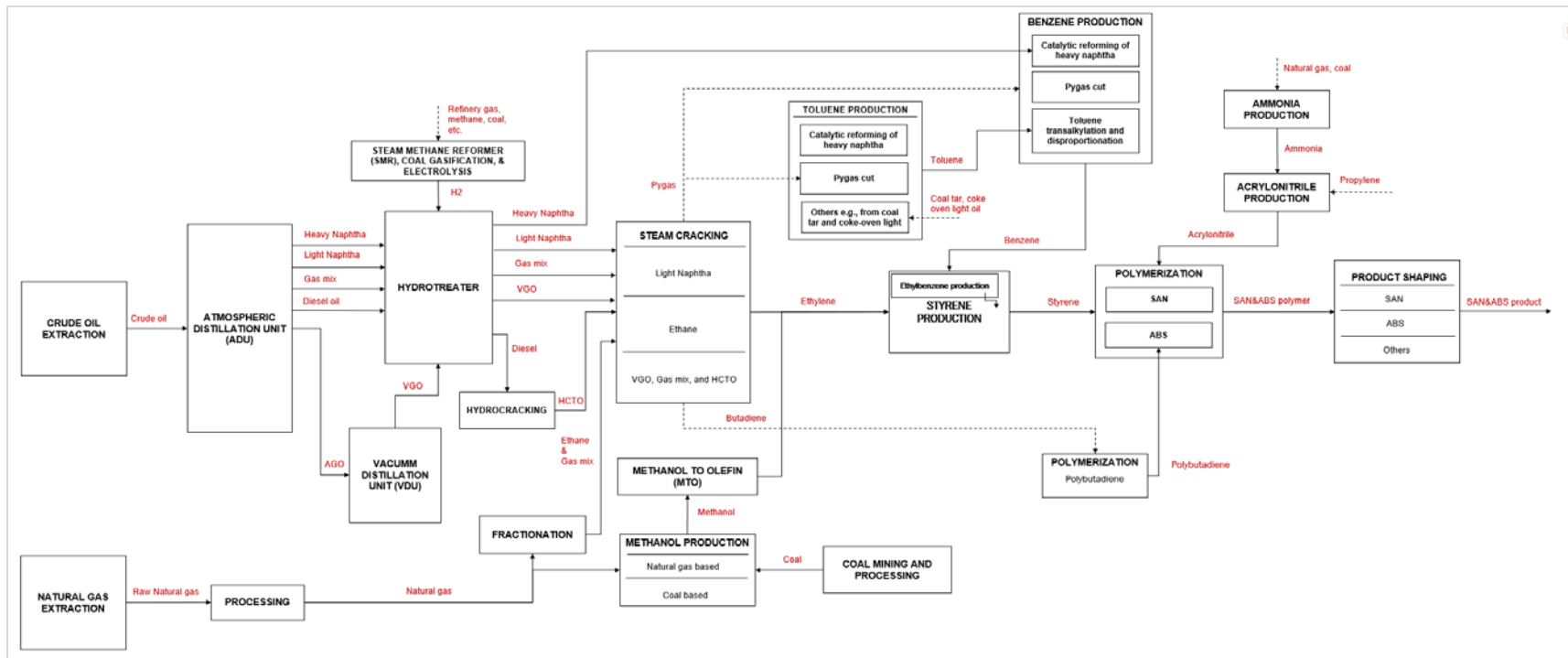
Figure 17. SAN&ABS production value chain and material flow chart.

Notes: ADU = atmospheric distillation unit, VDU = vacuum distillation unit, Gas mix = a mix of LPG, propane, and butene, LPG = liquid petroleum gas, AGO = atmospheric gas oil, VGO = vacuum gas oil, SMR = steam methane reformer, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, H_2 = Hydrogen, SAN = Styrene acrylonitrile, ABS = Acrylonitrile butadiene styrene.

- *Product Shaping:* PS, SAN and ABS products

PS can be used in an extremely wide range of applications. GPPS is an unmodified PS. HIPS is known as "toughened PS" or "rubber-modified PS." The mechanical characteristics of PS are improved via adding rubbers (i.e. polybutadiene). EPS and XPS contain a pentane or other blowing agent (as expansion gas) dissolved within the polystyrene.

GPPS and HIPS products together accounted for about 55% of global PS production in 2017, while foam PS products accounted for almost 35% (Figure 18). Most GPPS products are commonly manufactured by injection molding or extrusion of raw material PS resin [56]. HIPS is converted to products by injection molding, extrusion, and thermoforming [56]. EPS products are molded or cut into specific shapes and sizes, whereas XPS is an extruded sheet.

In contrast, ABS is commonly used in the automotive sector, home appliances, electronics, construction, transportation industries, and others. It is also the most common polymer used in 3D printing. Like most other thermoplastics, ABS products can be injection molded, blow molded, and extruded. SAN is commonly referred to as ABS without the butadiene. It has less impact strength and toughness than ABS.

Appendix Tables A.1 and A.2 contain the energy consumption data used in this analysis for PS, SAN, and ABS products.
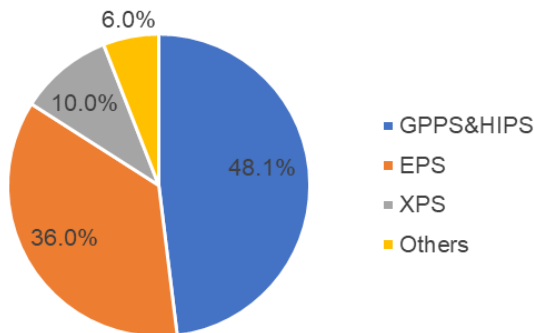
Figure 18. Share of different types of PS products in this analysis.

Notes: Others include film PS products such as OPS, a stretched XPS.
Source: [45,46,111,1112]

- *Polymerization:* PS, SAN and ABS products

PS polymers can be produced by bulk, solution, suspension, or emulsion polymerization of monomer styrene. Refer to Section 3.2 for a technical description of the polymerization processes.

GPPS is an unmodified polystyrene. Polymerization temperatures are between 110° and 180°C [56]. The styrene monomer conversion reaches 60-90 % of solid PS product [56]. The HIPS polymerization process is very similar to the GPPS process. The main difference is the addition of a rubber-like polybutadiene (a.k.a. butadiene rubbers) during polymerization. A typical rubber

content in commercial HIPS is about 5-15%, typically about 8% [56,113]. In this study, we assume 8% polybutadiene content in HIPS (in mass %). Polybutadiene is a synthetic rubber formed from the polymerization of the monomer 1,3-butadiene with an average conversion rate of 95% (butadiene to polybutadiene) [114].

Suspension polymerization is the most widely used process for large-volume production of EPS [53]. Polymerization temperatures are between 65° and 140°C, and styrene monomer conversions are reported to reach over 95 % for EPS products [49,56,115]. In this study, we assume that the styrene to EPS conversion rate is 97%. Pentane, a mixture of normal and isopentane, is added as a blowing agent during the course of polymerization [56]. On the other hand, XPS is manufactured by the extrusion of PS resin into boards in the presence of blowing agents (e.g., HFCs and HCFCs) [116].

ABS is a product of the systematic polymerization of monomers, acrylonitrile, butadiene, and styrene [117]. Proportions can vary from 15% to 35% acrylonitrile, 5% to 30% butadiene and 30% to 65% styrene [49,98,118]. In this study, it is assumed that the acrylonitrile, butadiene rubber (polybutadiene), and styrene content of global ABS production are 23%, 20%, and 49%, respectively, based on calibration data.[1] SAN, the predecessor of ABS, includes polymerization of two monomers, acrylonitrile (~25%) and styrene (~75%) [98].

Polybutadiene comes from polymerization of butadiene. About 1.05 tonnes of butadiene is required to make 1 tonne of polybutadiene [121]. Not much literature exists on the energy consumption of polybutadiene production. Two resources provide significantly different energy intensities: 12.8 GJ per tonne polybutadiene [49] and 25.9 GJ per tonne polybutadiene [121]. We assume that the energy intensity of polybutadiene production is 19.4 GJ per tonne polybutadiene. Appendix Tables A.3 and A.4 contain the energy consumption data used in this analysis.

In addition, methane (CH_4) is released during PS, SAN, and ABS production. Based on Hansen et al. [113], we assume that 0.07 kg CO_2e per tonne PS/SAN/ABS is emitted during production.

- *Monomer production: Styrene, acrylonitrile, propylene, benzene, toluene, ethylene, pygas*

Styrene:
Styrene is the main monomer that is used to make PS, SAN, and ABS. Around 85% of styrene is produced by the dehydrogenation of ethylbenzene using steam at 580-630°C [122]. In this process, ethylbenzene is treated with oxygen to form the ethylbenzene hydroperoxide. In addition, the production of styrene from pygas is also performed on a limited scale. Styrene is also co-produced commercially in a process known as POSM (styrene monomer/propylene oxide). Styrene can also be produced from other feedstocks such as butadiene and toluene [123]. However, both butadiene and toluene-based styrene productions are not commercially available yet [123]. In the absence of additional information on other production types, we assume that pygas and POSM together produce about 15% of styrene.

Table 3 summarizes energy consumption of the styrene production processes from the literature, along with our assumptions.

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[1] About one-third of global acrylonitrile production is for ABS [119,120].

Table 3. Styrene production energy consumption by production type

Styrene production	Literature range	This study
Dehydrogenation of EB (incl. EB production)	8.3-10.3 GJ/tonne styrene	
POSM	16.8 GJ/tonne styrene	
Pygas	8.3 GJ/tonne styrene	
Average	N/A	9.6 GJ/tonne styrene

Source: [50,124]

In addition, about 0.5 kg ethylene/kg styrene and 1.1 kg benzene/kg styrene are used during the production of styrene based on Russo et al. [49] and Hansen et al. [113].

In addition, elevated risks of cancer were found among workers with higher exposure to styrene [125].

Acrylonitrile:
Acrylonitrile is used for SAN and ABS production and is produced by the reaction of propylene with ammonia and oxygen over a temperature of 400-510°C and a pressure of 150-300 kPa [126]. The propylene conversion is 90-98% [49,127,128]. 0.7-1.5 GJ of energy are required for the production of 1 tonne of acrylonitrile by the ammoxidation process [126]. In this analysis, we assume the energy intensity of the process is 1.1 GJ electricity per tonne acrylonitrile. In addition, 1.04 kg propylene/kg acrylonitrile and 0.8 kg ammonia/kg acrylonitrile are used during the production of acrylonitrile, based on Morales-Mora et al. [126], Trangwachirachai and Lin [127], and Sampson [128].

Propylene, ethylene, benzene, pygas, and toluene:
Propylene is used for the production of acrylonitrile. Benzene and ethylene are used for ethylbenzene/styrene production. Toluene is used for benzene production via transalkylation and disproportionation of toluene. Pygas is used as a feedstock for aromatic extraction of benzene from a pyrolytic cracking process called "pygas cut." See Section 3.3 and 5.4.4 for details about the ethylene, benzene, and toluene production processes.

- *Other chemical compounds production: Ammonia, methanol*

Ammonia:
Ammonia is consumed for acrylonitrile (for SAN and ABS). See Section 3.4.5 for details about ammonia production processes.

Methanol:
Methanol is used for ethylene production (from MTO). See Section 3.5.1 for details about the methanol production processes using different feedstocks.

- *Hydrocarbon production: Toluene, naphtha, ethane, "gas mix", VGO, and HCTO*

Toluene, light and heavy naphtha, ethane, gas mix, VGO, and HCTO are the hydrocarbons used in production of PS, SAN, and ABS. See Section 3.4 for details about the production of these hydrocarbons.

- *Extraction and/or mining of fossil fuels:* Crude oil, natural gas, and coal

Modeling of GHG emissions related to the extraction, fracking, and mining of crude oil, natural gas, and coal for the feedstock and fuel energy needs of PS, SAN, and ABS plastic production is defined in Section 3.6.

2.6. Polyurethane

PUs are thermosets, which is a special group of polymeric materials that are in many ways different from most other plastic types. Thermoset polymers react to become permanently rigid when heated or mixed with a catalyst [6]. PUs can be produced in various forms, e.g., foams and elastomers, and used in a variety of markets, such as paints, liquid coatings, elastomers, insulators, elastic fibers, foams, and integral skins [27, 129].

Figure 19 shows the production flow chart of PU with input/output products and process technology details. PU polymers are typically produced through the reaction of a diisocyanate with a polyolefin (polyol). Toluene diisocyanate (TDI) and methylene diphenyl diisocyanate (MDI) are organic isocyanates that are used as key inputs to the industrial-scale production of PUs [98].

Figure 19. PU production value chain and material flow chart.

Notes: ADU = atmospheric distillation unit, VDU = vacuum distillation unit, Gas mix = a mix of LPG, propane, and butene, LPG = liquid petroleum gas, AGO = atmospheric gas oil, VGO = vacuum gas oil, SMR = steam methane reformer, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, H2 = hydrogen, EO = ethylene oxide, PO = propylene oxide, CO = carbon monoxide, TDI = toluene diisocyanate, MDI = methylene diphenyl diisocyanate, Polyol = polyolefins, NaCl = sodium chloride, PU = polyurethane. Please note that other production processes of propylene, e.g., FCC and PDH are not presented in the chart due to space limitations, but included in the modeling and analysis.

- *Product Shaping:* PU products

PUs can be grouped into several different classes based on their desired properties: foams, elastomers, binders, coating, adhesives, sealants, and others [129]. As illustrated in Figure 20, the principal consumption of PUs is in the form of foams. The main types of PU foams are flexible foams and rigid foams, but other classifications can also be attributed to PU foams, such as flexible PU slabs, flexible molded foams, reaction injection molding (RIM), carpet backing, or two-component formulations [128].
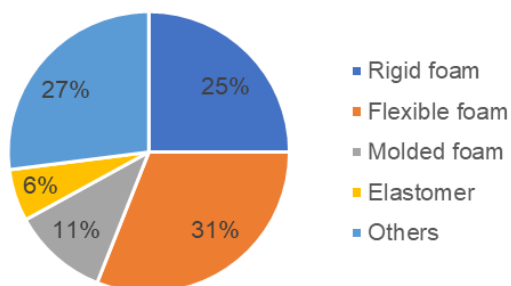
Figure 20. Share of different types of PU products.

Notes: "Others" could include binders, adhesives and sealings, coatings, and so on.
Source: [27,128,129]

- *Polymerization:* PU and polyol polymers

A PU polymer comprises long chains of polyols and diisocyanates (i.e., TDI and MDI) linked by urethane bonds and short diol chain extenders [130]. Polymerization occurs via a condensation reaction of diisocyanate and polyol to form a crosslinked PU. TDI is commonly used in the production of flexible PU foams, elastomers, coatings, adhesives and sealants [27,98]. In contrast, MDI is used in the production of rigid PU foams and elastomers (in the form of pure MDI) [27,98]. Polyols can be either polyether polyols or polyester polyols [27].

Table 4 summarizes the chemical material input per tonne of PU polymer assumed in this analysis. It is also assumed that 1.5 GJ of electricity is consumed for the production of a tonne of PU polymer, based on Russo et al. [49] and Plastics Europe [98].

Table 4. Material inputs for different types of PU polymers assumed in this analysis

	Input/PU polymer
Rigid foam	0.6 tonne MDI/tonne rigid foam
	0.4 tonne polyol/tonne rigid foam (40% polyether; 60% polyester)
Flexible foam	0.1 tonne TDI/tonne flexible foam
	0.7 tonne polyol/tonne flexible foam (100% polyether)
	0.1 tonne MDI/tonne flexible foam
Elastomer	0.2 tonne pure MDI/tonne elastomer
	0.01 tonne TDI/tonne elastomer

	0.4 tonne polyol/tonne Elastomer (55% polyether, 45% polyester)
Others	0.5 tonne MDI/tonne other PUs
	0.3 tonne polyol/tonne Other PUs (70% polyether, 30% polyester)
	0.2 tonne pure MDI/tonne other PUs
	0.1 tonne TDI/tonne other PUs

Source: [27,49,98]

Polyols:

Ethylene oxide (EO) and more commonly propylene oxide (PO) are used in the production of polyols. On global average, approximately 0.8 tonnes of PO per tonne of polyol and 0.1 tonnes of EO per tonne of polyol are used in polyol production [47,131]. In addition, polyol production uses about 17.7 GJ per tonne of thermal energy and 0.15 GJ per tonne of electricity [49].

Various processes can be used to produce POs; some of these are more energy intensive than others. The variation in EO production is less. Table 5 summarizes the assumptions for input requirement, energy consumption, and global production shares for different production processes used for PO and EO production in this analysis.

Table 5. Input requirement, energy consumption, and production share of PO and EO production processes, assumed in this analysis

Production process	Input/output	Energy consumption	Global production share
PO			
Chlorohydrin for PO	0.8 tonne propylene/tonne PO	31.7 GJ/tonne PO	35%
	1.1 tonne chlorine/tonne PO		
Hydro peroxidation for PO	0.4 tonne propylene/tonne PO	28.6 GJ/tonne PO	8%
	0.9 tonne hydrogen peroxide/tonne PO		
SMPO for PO	0.8 tonne ethylbenzene /tonne PO	16.8 GJ/tonne PO	40%
Other processes for PO	0.79 tonne other products (e.g., cumene) /tonne PO	33.1 GJ/tonne PO	17%
EO			
All processes for EO	0.8 tonne ethylene/tonne EO	10 GJ/tonne EO	100%

Notes: PO = propylene oxide, EO = ethylene oxide, SMPO = Styrene monomer/propylene oxide.
Source: [51,98,132]

- *Monomer production:* MDI, TDI, ethylene, propylene, ethylbenzene

Toluene diisocyanate:
TDI is produced in three steps: (1) nitration of toluene for DNT, (2) dinitrotoluene (DNT) hydrogenation to toluenediamine (TDA), and (3) phosgenation of TDA for TDI. The nitration of toluene to DNT is achieved by the reaction of toluene with nitric acid and a catalyst [133]. TDA is produced via a catalytic reduction of DNT under hydrogen pressure (hydrogenation). TDA is treated with phosgene (i.e., carbonyl chloride) under controlled temperature and pressure conditions to produce TDI. TDI production, excluding phosgene production, requires an energy consumption of about 11 GJ per tonne [133]. Production of 1 tonne of TDI also requires about 0.3 tonne toluene, 0.6 tonne nitric acid, and 1 tonne phosgene [133-136].

Methylene diphenyl diisocyanate:
MDI is made from the reaction of aniline and formaldehyde using an acidic catalyst such as hydrochloric acid and then treated with phosgene. Production of 1 tonne of MDI requires about 0.5 tonne aniline, 0.2 tonne formaldehyde, and 0.6 tonne phosgene [133-136]. MDI production requires an energy consumption of about 4.2 GJ/tonne [49,98,137].

Ethylene, propylene, and ethylbenzene:
Ethylene and propylene are used for EO and PO production. Ethylene is also used for ethylbenzene production, together with benzene. The energy intensity of ethylbenzene production is assumed to be 3.5 GJ per tonne of ethylbenzene [99]. See Section 3.3 for details about the ethylene and propylene production processes.

- *Hydrocarbon production:* Naphtha, ethane, "gas mix", VGO, HCTO, toluene, and benzene

Naphtha (both light and heavy), ethane, gas mix, VGO, HCTO, toluene, and benzene are the hydrocarbons used in the production of PU. See Section 3.4 for details about the production of these hydrocarbons.

- *Other chemical compounds production:* Phosgene, formaldehyde, nitric acid, aniline, ammonia, chlorine, methanol, CO,

Phosgene:
Phosgene is manufactured from a reaction of carbon monoxide (CO) and chlorine gas in the presence of a catalyst [134]. The PU industry consumes almost 85% of total phosgene production [134,136]. Consumption of phosgene for MDI and TDI accounted for 55% and 27%, respectively, of total demand in 2021 [136]. Production of 1 tonne of phosgene requires about 0.4-0.5 GJ of energy [137]. About 15% of this energy demand is from electricity [137].

Formaldehyde:
Formaldehyde is produced industrially by the catalytic oxidation of methanol in a conversion zone maintained at a temperature within a range of 450° to 700°C [138]. Production of 1 tonne of formaldehyde requires about 0.9 tonne methanol and 7.5 GJ energy [139-141].

Aniline, nitric acid and nitrobenzene production:

Aniline is formed by the hydrogenation of nitrobenzene in the presence of a copper-chromium or copper-silica catalyst, or by vapor stage ammonolysis of phenol and ammonia. Nearly all nitric acid is manufactured by the high-temperature catalytic oxidation of ammonia [142]. The liquid ammonia is evaporated, superheated, and sent with compressed air to a convertor containing catalysts. Nitrobenzene is manufactured commercially by the direct nitration of benzene.

Ammonia:
See Section 3.4.5 for details about ammonia production processes.

Methanol:
See Section 3.5.2 for details about the methanol production processes using different feedstocks.

CO:
CO is produced on an industrial scale by the partial oxidation of hydrocarbon gases from natural gas or by the gasification of coal and coke.

- *Extraction and/or mining of fossil fuels: Crude oil, natural gas, and coal*

Modeling of GHG emissions related to the extraction, fracking, and mining of crude oil, natural gas, and coal for the feedstock and fuel energy needs of PU plastic production is defined in Section 3.6.

3. Production processes and technologies

In this section, we summarize some of the basic processes and technologies used commonly in the production of primary plastics. These are the processes and technologies that are used in the production of more than one polymer. Processes that are specific only to the production of a particular polymer are described in the relevant subsections in Section 2.

3.1. Product shaping processes

A range of processing technologies are used to convert raw polymers into the final finished product. This section defines the most common manufacturing processes used to shape polymer pellets into finished plastic products. These processes consume varying quantities of energy, but typically in the range of 3-22 GJ per tonne of finished plastic product. The amount of energy consumption is fundamentally influenced by the type and complexity of the process and the polymer, as well as the type and specification of the machines and devices used (e.g., hydraulic vs. all-electric injection molding). For polymers with a wider range of energy intensities in the literature, we use the weighted average. Table A.1 in the Appendix lists the energy intensities assumed for the different product-shaping processes for each plastic polymer analyzed in this study.

3.1.1. Blow molding

Blow molding of plastics is a manufacturing process for the forming of a hollow object by inflating or blowing a thermoplastic molten tube in the shape of a mold cavity. The material then is cooled until it reverts to a solid finished part. The polymers commonly used in blow molding processes include LDPE, HDPE, and PP. Examples of products would include various types of

bottles, containers, cans, hoses, and planters. The typical energy intensity of the blow molding process ranges from 5 to 9.4 GJ per tonne for different plastic polymers in the literature [143-146].

3.1.2. Injection molding

Injection molding forces melted polymer into a mold under high pressure [147]. Similar to blow molding, the material is cooled until it reverts to a solid, then the mold is opened and the finished part is extracted. The most common plastic polymers used for injection molding are: all types of PE, PP, PVC, and PS. This method has produced solid parts such as electronic housings, bottle caps, containers, computers, television components, outdoor furniture, agricultural products, toys, and machinery components, among others. Injection molding is one of the most energy-intensive processes, with a process load of between 4.8 and 13 GJ per tonne, depending on hydraulic, all-electric, or hybrid injection [143,144,148,149]. About 55% of injection molding machines are hydraulic, 35% are all-electric, and 10% are hybrid [148,149].

3.1.3. Film extrusion

In this process, the polymer is melted in an extruder and the hot melt is pumped through a die to form a thin-walled tube which is simultaneously axially drawn and radially expanded [47]. Typical plastic polymers used in extrusion include but are not limited to all types of PEs, PP, PET, PS, and PVC. Polymer films are typically used in packaging such as shrink, stretch, barrier films, and frozen food packaging, and shopping bags. Typical energy demand during processing ranges between 1.6 and 9.6 GJ per tonne in the literature [143,144,148,149].

3.1.4. Other extrusion

Other extrusion processes, such as profile extrusion, have significantly higher energy intensity ratings and temperatures that often reach 200°C [145]. The molten plastic moves into and through a die which is responsible for giving the molten plastic its profile (shape). After cooling, the product is cut to length, spooled, or coiled and produces a distinctive plastic channel, such as profile or tube. The energy demand of other extrusion processes varies over a large range, depending on the process and polymer, and is listed as 5.5 to 21.6 GJ per tonne in the literature [143,148,149].

3.1.5. Fiber

Plastic fibers are plastics that have been spun into fibers or filaments and used to make fabrics, string, ropes, cables, and even optical fibers [150]. Some of the most recognizable plastic fibers are polyester (i.e., PET), nylon (i.e., polyamid (PA)), PVC, acrylic, and spandex (based on PU), although there are many more.

Synthetic fibers are produced through a process of spinning, where a polymeric liquid is extruded through fine holes called spinnerets. This is commonly called "monofilament extrusion." Typical energy demand during processing is about 6.3 GJ per tonne, depending on the polymer [143,151].

3.1.6. Thermoforming

Thermoforming is a plastic manufacturing process that involves heating a plastic sheet and forming it using a mold to specific shapes. The shaped plastic then gets cooled down and trimmed to result in the finished part. Thermoforming is applied to many types of plastics, such as PET, PES, PVC, ABS, and PS. Typical energy demand during processing is about 4.8 to 22 GJ per tonne, depending on the polymer [148,149].

3.2. Polymerization processes

Polymerization is the process used to create polymers from monomers. The plastic polymers are then used to make various kinds of plastic products. During polymerization, monomers (smaller molecules) are chemically combined to create larger molecules (or "a macromolecule") [152]. Hundreds of such macromolecules collectively form a polymer. There are two basic types of polymerization, chain-growth (or addition) and step-growth (or condensation) polymerization [152]. In chain-growth polymerization, a chain reaction adds new monomer units to the growing polymer molecule one at a time through double or triple bonds in the monomer. Some examples of polymers formed via chain-growth polymerization are PE, PP, PVC, and PS. On the other hand, condensation polymerization is a process that involves repeated condensation reactions between tri-functional or bi-functional monomers. Some examples of polymers formed via step-growth polymerization are PET and PU.

Generally, the reaction of monomers to polymers may be carried out by one of the following processes [56]:
- **Suspension (Slurry) polymerization**: In suspension polymerization, the chemical reaction takes place in droplets that are in suspension in a solvent. Typical products made by suspension processes are PE, PP, PVC, PS (HIPS and EPS), and others.
- **Bulk polymerization**: In bulk polymerization, the polymer is produced in a reactor where only the monomer and a small amount of an initiator are present. Typical products made by bulk processes are PE, PP, PVC, PS, PET (including polyester fibers), and others.
- **Emulsion polymerization**: In emulsion polymerization, the chemical reaction takes place in droplets that are in suspension in a solvent, as with suspension polymerization, but are also in emulsion structures called micelles, as well as in the solvent. Typical products made by emulsion processes are PS, SAN, ABS, PVC, and others.
- **Gas stage polymerization**: In gas stage polymerization, the monomer is introduced in the gaseous stage and put in contact with a catalyst deposited on a solid structure. Currently, gas stage processes are only applied to the polyolefins — PE and PP.
- **Solution polymerization**: In solution polymerization, the chemical reaction takes place in a solution of the monomer in a solvent. Typical products made by solution processes are PS, PE, and others.
- Polymerization of PU occurs via a condensation reaction of diisocyanate and polyol to form a crosslinked PU.

Please note that some co-facilities may perform the first round of forming (e.g. extrusion) to create pellets and/or filaments before sending them to plastic product shaping facilities. The energy intensity levels used for polymerization in this analysis (see relevant subsections in Section 2 for details) could not fully reflect the emissions associated with this first round of

forming. Such facilities would have additional GHG emissions associated with the first round of forming.

3.3. Monomer production processes

Ethylene, propylene, butadiene, benzene (which is actually a trimer)[17], LAOs, PTA, EG, ethylbenzene, styrene, VCM, acrylonitrile, MDI, TDI, PO, and EO are the main monomers used in the production of primary plastic polymers discussed in this report. While some of these monomers are only used production of one specific polymer and in this case are defined in their associated subsections in Section 2, some are used in production of multiple polymers. In this section, we define the monomers used in production of multiple polymers, namely ethylene, LAOs, and propylene. This section also defines the processes commonly used to produce them.

3.3.1. Monomers

- *Ethylene*

Ethylene is a common monomer that is used as an input to produce all polymers analyzed in this report, i.e., LDPE, LLDPE, HDPE, PP, PET, PVC, PS, SAN, ABS, and PU. Almost 90% of the ethylene is used for production of plastic polymers [153,154]. It is predominantly produced by steam cracking of hydrocarbons (i.e., light naphtha, ethane, VGO, HCTO, and other light hydrocarbon LPG gas mixes, e.g., propane and butane). A small share of ethylene is produced via MTO process. Currently, MTO accounts for around 3.5% of global ethylene production [155].

Global steam cracking of light naphtha and ethane accounted for roughly 40-45% and 30-35% of ethylene production in 2015, respectively [41,156]. The remaining 20-30% of ethylene production came from the steam cracking of VGO, HCTO, and other light hydrocarbon gas mixes, as well as the MTO process. In 2023, it is reported that about 36% of ethylene production came from steam cracking of naphtha and about 39% from steam cracking of ethane [155]. Table 6 provides details of the global ethylene production process shares assumed in this analysis.

Table 6. Distribution of global ethylene production by process and input raw material type assumed in this analysis

Production process and input material type	Global production share (%)
Steam cracking of light naphtha	36%
Steam cracking of ethane	39%
Steam cracking of gas mix (e.g., LPG, propane, butane)	16%
Steam cracking of HCTO	0.5%
Steam cracking of VGO	5%
Coal-based methanol-to-olefin (CMTO)	2%
Methanol-to-olefin (MTO) (other than coal)	1.5%

Notes: LPG = Liquid petroleum gas, VGO = vacuum gas oil, HCTO = hydrocracking tail oil, MTO = methanol-to-olefin, CMTO =. coal-based methanol-to-olefin.

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[17] Trimer is a polymer comprising three monomer units.

Source: [36,155,157,158]

- *Linear alpha-olefins*

Most linear alpha-olefins, such as 1-butene, 1-hexene, 1-octene, are commercially produced either through ethylene oligomerization or Fisher–Tropsch synthesis/catalytic cracking [159]. Oligomerization of ethylene to LAOs is performed in a bubble column reactor at temperatures between 50°C and 100°C [160]. In this analysis, energy intensity of this process is assumed to be 2 GJ per tonne of alpha-olefins. It is also assumed that 0.35 tonnes of ethylene is required for 1 ton of LAO [160].

- *Propylene*

Propylene is produced in three commercial grades: refinery grade, chemical grade, and polymer grade (which is used to produce polypropylene). More than 80% of polymer grade propylene in the market is produced by steam cracking process and fluid catalytic cracking (FCC) units in petroleum refineries (see Figure 21). However, due to the low yields of propylene from these processes (as defined below in subsections 3.3.2), new production processes such as propane dehydrogenation (PDH), MTO or MTP, and metathesis and superflex processes have been developed or are being developed.
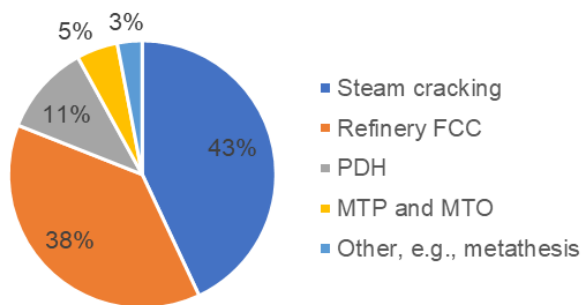
Figure 21. Distribution of global propylene production by production process type in 2019.

Notes: FCC = fluid catalytic cracking, PDH = Propane Dehydrogenation, MTP = methanol-to-propylene, MTO = methanol-to-olefin.
Source: [161-163]

3.3.2. Production of monomers

- *Steam cracking*

Steam cracking is a process in which gaseous or liquid hydrocarbons – such as light naphtha, ethane, distillate fuel oils (e.g., VGO, HCTO), and other light gas mixtures (e.g., LPG, propane, butane) – are broken down into smaller hydrocarbons with steam and then briefly heated in a furnace. Typically, the reaction temperature is very hot (around 850°C). It is the principal industrial method for producing olefins, such as ethylene and propylene [164]. The type of hydrocarbon used as raw material generally depends on geography and cost and availability of the feedstock.

Steam cracking produces a range of other high value chemicals (HVCs) such as butadiene, benzene, and toluene next to ethylene and propylene, as well as gases such as hydrogen and CH_4. Steam cracking of different hydrocarbons produces different product yield ratings. For example, the ethylene yield of light naphtha steam cracking ranges between 27-34%, while the ethane steam cracking yield is much higher, at 80-86% (see Table 7).

The energy intensity of steam cracking processes has been studied extensively in the recent literature. Because steam cracking mostly targets ethylene production, most studies present energy intensity as the energy consumed per tonne of ethylene production (i.e., GJ/tonne ethylene) (e.g., [38],[39],[41],[54],[165],[166]). With this approach, other outputs are assumed as by-products of ethylene production. Some studies present energy intensity as the energy consumed per tonne of HVC (i.e., GJ/tonne HVC) (e.g., [37],[41],[49],[51],[54]). In this study, we follow the latter approach and use the mass allocation method to distribute the energy consumption and emissions generated over the different outputs from the steam cracking process.

A high level of uncertainty surrounds co-produced gases. Most facilities repurpose these gases internally for heat demand, while some use them to convert to electricity in gas-fired captive power plants. There is also a literature discussing fugitive CH_4 emissions during the steam cracking processes [41,167]. Most literature on energy consumption includes the negative energy from internal repurposing of co-produced gases for heat demand in their final energy intensity numbers [36-38,41,49,51,54,165,166]. The energy consumption levels presented in Table 7 capture this discount, so our baseline projections are based on discounted energy consumption. However, in this analysis we do not specifically assume that H2 and CH4 are used for electricity generation purposes due to uncertainty in the data. We consider that the citation used for the average global CO_2 emission intensity of electricity generation will reflect their impact. Appendix Tables A.6 and A.7 contain the yields from other hydrocarbons and shares of fuels used in this analysis.

Table 7. Process yields, energy consumption, and fugitive emissions from light naphtha and ethane-based steam cracking

Light Naphtha-based steam cracking		
	Literature range	This study
Ethylene (Yield (%))	27.3-34.1%	30.4%
Propylene (Yield (%))	12.3%-17.5%	15.9%
Butadiene (Yield (%))	3.6%-8.7%	4.9%
Benzene (Yield (%))	4.2%-13.3%	7%
Toluene (Yield (%))	1.6%-4.6%	3.2%
Xylene (Yield (%))	1.3-2.6%	1.4%
Energy consumption (GJ/tonne HVC)	16.5-22 GJ/tonne HVC	18.4 GJ/tonne HVC
Fugitive CH4 emissions (tCO₂e/t HVC)	0.04 tCO₂e/t HVC	0.04 tCO₂e/t HVC
Ethane-based steam cracking		
	Literature range	This study
Ethylene (Yield (%))	79.6-86%	82.4%
Propylene (Yield (%))	1-2%	1.6%

Butadiene (Yield (%))	1-2.3%	1.2%
Energy consumption (GJ/tonne HVC)	14.5-19 GJ/tonne HVC	17 GJ/tonne HVC
Fugitive CH4 emissions (tCO₂e./t HVC)	0.1-0.2 tCO₂e/t HVC	0.2 tCO₂e/t HVC

Notes: Yields are on mass basis. The yield levels used in this study are based on the literature average. The table does not present yield for pygas from naphtha cracking, but the yields from aromatic compounds from it. There is also a negligible amount (~1-2%) of BTX production from ethane cracking, which we do not apply in this analysis. Please see Appendix Table A.6 for other hydrocarbon-based steam cracking data. HVC = High value chemical. Source: [38-41,49,54,114,158,165-172]

- *Fluid catalytic cracking*

FCC is one of the most commonly used processes in refineries, in which heavy feedstocks such as VGO or residual oil are cracked into propylene and other lighter products (e.g., gasoline). Even though its propylene yields suffer [173,174], traditional FCC became popular in propylene production due to its economics compared to steam cracking [169]. In the last decade or so, there has been an increasing interest in maximizing propylene yield of FCC units [33,159,167-169]. FCC unit has the ability to produce high yields under selected operating conditions. For example, high propylene FCC units can produce approximately10% propylene yield and high selectivity FCC units can produce 15-25% propylene yield compared to about 6% propylene yield in traditional FCC units [173,174].

FCC operates around 550°C and does not require extreme cooling for the separation of propylene from LPG [49]. Therefore, the energy consumption of producing propylene from FCC is much lower than that of steam cracking [51,175]. According to the literature, producing 1 tonne of propylene via FCC requires around 8.5-11 GJ of final energy per tonne of propylene [51,176-178], depending on the achieved yield. In this study, we assumed a global average of 13% yield and an energy consumption of 9.3 GJ per tonne of propylene for the FCC process.

- *Methanol-to-olefins*

The MTO process is used to convert methanol to olefins (i.e., ethylene and propylene). This process is known as non-petroleum-based olefin production since the methanol used in the process is synthesized from carbon-rich feedstocks, such as natural gas, coal or coke gas, hydrogen, and a catalyst [179].[18] The olefin yield of the MTO process is about 40% [180-182]. In this study, we assume the ethylene and propylene yields of the MTO process are 15% and 25%, respectively, based on Jasper and El-Halwagi [182].

In addition to MTO, MTP is used in the production of propylene. The differences between the MTO and MTP processes lie in the degree of propylene selectivity and the type of catalyst used for each process [182]. As a result, propylene yields from these processes are different. According to Jasper and El-Halwagi [182], the propylene yield of MTP is over 30%.

For MTO technologies, the average unit energy consumption is in the range of 5 to 8 GJ per tonne of ethylene and propylene mixture [51]. The MTP process requires about 7.6 to 13.2 GJ per tonne of propylene. Methanol production requires an additional 14 to 24 GJ per tonne of

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[18] Hydrogen can also be produced through electrolysis. In that case, it would not be a carbon-rich production.

methanol, depending on the feedstock used (see Section 3.5.1). Appendix Table A.7 provides further technical background on fuel use.

Table 8. Energy consumption of MTO and MTP processes assumed in this analysis

Production processes	This study
MTO	6.3 GJ/tonne olefin
MTP	12.3 GJ/tonne propylene

Note: In this table, olefin in MTO stands for a mixture of ethylene and propylene.

Vented and fugitive CH_4 emissions from the MTO and MTP processes are reported in some literature [183]. We assume that 8% of the GHG emissions from MTO and MTP processes are CH4 emissions (based on Zhao et al. [183]).

- *Propane dehydrogenation*

PDH technology converts propane into propylene with a significantly higher propylene yield (about 85%) [161,174,184-186]. The process is highly endothermic and is usually carried out at high temperature (480-600°C) and low pressure. The average energy consumption of this process is about 13.5 GJ per tonne of propylene [51].

- *Metathesis and Superflex*

The metathesis reaction is the reaction of butene-2 with ethylene to produce propylene. The ethylene-to-butene feed ratio to the reactor is controlled to minimize by-products and maintain the per-pass butene conversion above 60% [186]. The typical yield from this process ranges between 40% to 99%, depending on the feed ratio. In this study, we assume that the global average propylene yield rate for the metathesis reaction is 70% and the energy consumption is 6.5 GJ per ton of propylene [51].

3.4. Hydrocarbon refining and processing

Most hydrocarbons must be separated and processed from crude oil and natural gas before they are used in plastic production. Key hydrocarbons used in plastic production are light and heavy naphtha, ethane, gas mix, VGO, HCTO, p-xylene, and toluene. Most of these hydrocarbons are exclusively derived from petroleum refineries and natural gas processing plants.

- *Petroleum refineries*

Crude oil requires multiple intermediate steps in refineries to be transformed into petroleum products. The refining process involves the separating, cracking, reforming, treating, and blending of hydrocarbon molecules. Petroleum refinery operations generally start in an atmospheric crude distillation unit (ADU). Crude oil is heated in the ADU tower to 370-380°C and split into compounds of differing molecular structure (fractions) in a distillate tower at atmospheric pressure [187]. This way, the ADU separates lighter hydrocarbons from heavier oils based on their respective boiling points. Naphtha (both light and heavy) and LPG gas mix are two of the initial refinery products that come from ADU units.

Heavier oils, including atmospheric gas oil (AGO) and diesel oil, require further processing. AGO from the bottom of the ADU tower continues to the vacuum crude distillation unit (VDU), where heat of up to 400°C is applied under vacuum conditions to further separate products to VGO [98].

A total of five products from the ADU – light naphtha, heavy naphtha, diesel oil, and gas mix –, and VDU – VGO – then enters the hydrotreating process. Hydrotreating is a process that removes impurities such as nitrogen and sulphur compounds from hydrocarbon streams. During hydrotreating, the products are selectively reacted with hydrogen in the presence of a catalyst at relatively high temperatures and moderate pressures [188]. Diesel oil is further processed in a hydrocracking unit in addition to the hydrotreatment process to be converted to HCTO.

The catalytic reforming process is used in the production of high-octane components of automobile gasolines and light aromatic hydrocarbons –BTX. Catalytic reforming processes involve dehydrogenation of heavy naphtha to yield a mixture of aromatics and paraffins (also called "reformate"). Individual aromatics are then recovered by distillation, washing with nitric acid, and re-distillation [189]. BTX products are also produced by different production routes (see subsection 3.4.2 for details).

Table 9 shows the mass shares of crude oil refinery outputs that are currently used as feedstock in plastic production. The shares are calibrated based on the total feedstock demand from plastic production (modelling output of this study) and total crude oil processed in refineries in 2019 globally (i.e., 4441.5 million tonnes of oil equivalent (Mtoe) crude oil [190]).

Table 9. Mass shares of crude oil refinery outputs used in plastic production, based on calibration

Petroleum product	Mass share (%)
Light naphtha	3.5%
Heavy naphtha	1.9%
Share of gas mix	0.7%
Share of Diesel oil	0.1%
Share of AGO	1.2%

Note: The shares in this table only represent feedstock mass allocation, and do not include fossil fuel use for process energy need.

- *Natural gas processing*

Natural gas goes through a multi-step process to be converted into natural gas liquids (NGLs) such as ethane and gas mix of propane and butane. The main steps of natural gas processing include acid gas removal, dehydration, hydrocarbon recovery via compression, and liquids processing (i.e., fractionation).

The first unit operation in natural gas processing is acid gas removal, which removes hydrogen sulfide (H_2S), a toxic and corrosive gas, prior to further natural gas separation [41]. After acid gas removal, the gas stream is sent to a dehydration unit. In the hydrocarbon recovery unit, CH_4 is separated from NGLs at a low temperature. Electricity is used in the compression stage (to raise pressure) and in the refrigeration stage (to condense NGLs). Liquids processing separates

NGLs into ethane, propane, and butane using fractionation trains composed of a deethanier, depropanizer, and debutanizer. In the depropanizer and debutanizer, heat is provided by combusting natural gas in a reboiler for distillation, and electricity is provided for cooling of condensing products [41].

Table 10 shows the mass shares of natural gas processing and fractionation outputs that are used in plastic production as feedstock in the current production structure. The shares are calibrated based on the total demand from plastic production (modelling output of this study) and total natural gas produced in 2019 globally (i.e., 3905.8 billion cubic meters (bcm) (~2829.8 Mt) natural gas [191]).

Please note that propane can be a product of both petroleum refinery and natural gas processing. Table A.8 provides the shares of global propane production from petroleum refineries and natural gas processing plants assumed in this analysis.

In addition to ethane and gas mix, natural gas is also used to produce methanol and ammonia. Methanol is used for ethylene (from MTO), formaldehyde (for PU), and acetic acid (for PET) production, and ammonia is required in ABS and PU production.

Table 10. Mass shares of natural gas processing and fractionation outputs used in plastic production, based on calibration

Natural gas product	Mass share (%)
Ethane	2.8%
Gas mix	0.7%

Note: The shares in this table only represent feedstock mass allocation, and do not include fossil fuel use for process energy need.

3.4.1. Energy consumption and GHG emissions from petroleum refineries and natural gas processing facilities

Crude oil refining and natural gas processing processes are energy-intensive, requiring considerable amounts of direct or indirect heat (see Table 11). According to International Energy Agency (IEA) [192], oil and gas operations account for nearly 15% of energy-related global GHG emissions. Table 10 lists the unit energy consumption of oil and gas operations derived from the literature and used in this analysis. Appendix Table A.8 provide more information on fuel use in crude oil refineries and natural gas processing plants assumed in this analysis.

Table 11. Energy consumption (GJ/tonne product) of petroleum refinery and natural gas processing plant processes

	Energy consumption (GJ/tonne product)	
	Literature range	This study
Petroleum refineries		
Atmospheric crude distillation	0.7-1.5 GJ/tonne crude oil	1.02 GJ/tonne crude oil

Vacuum crude distillation	0.4-0.9 GJ/tonne product	0.7 GJ/tonne product
Hydrotreating	0.7-1.7 GJ/tonne product	0.9 GJ/tonne product
Hydrocracking	1.2-2.7 GJ/tonne product	1.9 GJ/tonne product
Natural gas processing		
Acid gas removal, dehydration, hydrocarbon recovery and compression	1.6-2 GJ/tonne natural gas	1.9 GJ/tonne natural gas
Liquids processing (fractionation)	2.2 GJ/tonne natural gas	2.2 GJ/tonne natural gas

Source: [41,176,193-197]

Crude oil refineries produce process-based GHG emissions in addition to fuel combustion emissions. Figure 22 shows the sources of petroleum refining emissions globally. Natural gas processing for NGLs also releases fugitive natural gas emissions in terms of flared or vented emissions. These emissions can make up to about 10% of total emissions from NGL production globally [41,194,198,199]. Appendix Table A.9 contains the process-based emission rates assumed in this analysis.

It is also assumed that global average efficiency of the petroleum refineries and natural gas processing plants are 86% and 95%, respectively, based on DOE [193] and Lacroix et al. [200], respectively.
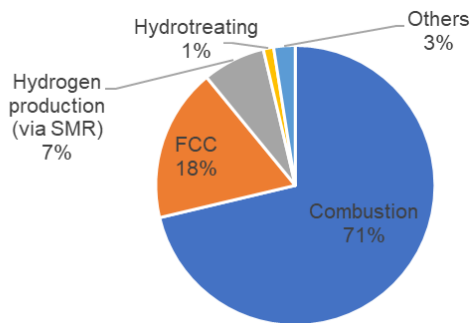
Figure 22. Shares of petroleum refining emissions by source.

Notes: The percent shares in the figure represent the recent global average, not a specific refinery. The variations of GHG emissions from refineries is mainly caused by the type of refinery configuration, the type of crude oil, and many other geographical factors. Combustion includes combustion of fossil fuels for processes and onsite electricity generation and distribution losses. Emission shares other than combustion represent process-based emissions. FCC = fluid catalytic cracking; SMR = steam methane reformer.
Source: [193,194,201,202]

3.4.2. Benzene, toluene and p-xylene production

BTX refers to mixtures of benzene, toluene, and the three xylene isomers, all of which are light aromatic hydrocarbons used commonly in the production of plastics. P-xylene is one of the xylene isomers used in the production of PET. Toluene is used for PET, PS, SAN, ABS, and PU, while benzene is required for PS, SAN, ABS, and PU production. This section describes the common processes used to produce BTX.

- *Benzene*

Approximately 50% of the global benzene supply comes from the catalytic reforming of heavy naphtha, followed by toluene-based processes at 25%, and pygas cut at 25% [203,204]. Toluene-based processes, namely transalkylation and disproportionation of toluene, are often used to convert toluene into benzene along with p-xylene [205-210]. Pygas is a highly aromatic intermediate hydrocarbon produced by the steam cracking of light naphtha and VGO along with ethylene, propylene, and butadiene [211]. It is often used as a highly aromatic hydrocarbon feedstock for the aromatic extraction of benzene, toluene, and p-xylene from a pyrolytic cracking process called "pygas cut."

Table 12 shows the process yields and unit energy consumptions of production technologies used to produce benzene, along with the data assumed in this analysis.

Table 12. Benzene yields and unit energy consumption from different production processes

	Yield (%)		Energy consumption	
	Literature range	This study	Literature range	This study
Catalytic reforming	3-7.8%	5.7%	4.1 GJ/tonne benzene	4.1 GJ/tonne benzene
Transalkylation and disproportionation of toluene	42%	42%	4.5 GJ/tonne benzene	4.5 GJ/tonne benzene
Pygas cut	33%	33%	5.5 GJ/tonne benzene	5.5 GJ/tonne benzene

Source: [53,212,213]

- *Toluene*

Approximately 70% of the global toluene supply comes from the catalytic reforming of heavy naphtha, followed by pygas cut at 25%, and other materials at 5% [214-216]. Even though catalytic reforming is the most common production for toluene, only a small fraction of the reformate is used for isolation of the toluene; the bulk of the unseparated toluene in the reformate is used for gasoline blending [217]. With pygas cut, toluene is isolated from pyrolysis gasoline by distillation, removal of olefins and di-olefins, and redistillation. As mentioned earlier, pygas is a product of steam cracking of light naphtha and VGO.

Toluene can also be obtained as a product during styrene production when ethylbenzene is dehydrogenated, and also from other products such as coal tar and coke-oven light oil. In this analysis, we do not consider toluene production from styrene production as the global share is fairly small. Table 13 shows the process yields and unit energy consumptions of production technologies used to produce toluene, along with the data assumed in this analysis.

Table 13. Toluene yields and unit energy consumption from different production processes

	Yield (%)		Energy consumption	
	Literature range	This study	Literature range	This study
Catalytic reforming	13-26%	20%	2-2.4 GJ/tonne toluene	2.2 GJ/tonne toluene
Pygas cut	19-20%	20%	5.5 GJ/tonne toluene	5.5 GJ/tonne toluene

| Other materials e.g., coal tar and coke-oven light oil | 18% | 18% | 2.4-4.4 GJ/tonne toluene | 2.4 GJ/tonne toluene |

Source: [51,206,212,218]

- *P-xylene*

Globally, most p-xylene (~79%) is produced by catalytic reforming of heavy naphtha [95,205]. Approximately 17% is produced by toluene-based processes, followed by about 4% from pygas cut [205,219].

Both catalytic reforming and pygas cut have two separate stages when producing p-xylene. In the first stage, xylene isomers are separated along with other aromatics, e.g., benzene and toluene [98]. In the second stage, p-xylene is separated from other isomers by more energy-intensive processes such as adsorption or crystallization processes. The product stream from the catalytic reformer usually consists of 18-20% of mixed xylenes [212]. Mixed xylene usually contains about up to 20% p-xylene [206,207]. Table 14 shows the process yields and unit energy consumptions of production technologies used to produce p-xylene, along with the data assumed in this analysis.

Table 14. P-xylene yields and unit energy consumption from different production processes

| | Yield (%) | | Energy consumption | |
	Literature range	This study	Literature range	This study
Catalytic reforming	3.1-5.3% p-xylene	4.2% p-xylene	14.7 GJ/tonne xylene	14.7 GJ/tonne p-xylene
Pygas cut	4-15% p-xylene	8% p-xylene	14.1 GJ/tonne p-xylene	14.1 GJ/tonne p-xylene
Transalkylation and disproportionation of toluene	~97% p-xylene	97% p-xylene	22.9-31.8 GJ/tonne p-xylene	27.3 GJ/tonne p-xylene

Note: The data on the table includes separating p-xylene from mixed xylene. Mixed xylene usually contains about up to 20% p-xylene and energy intensity of separating p-xylene from mixed xylenes are about 8.56 GJ/tonne p-xylene.
Source: [51,96,206,209-214]

3.5. Other chemicals production *(non-hydrocarbon)*

Methanol, ammonia, acetic acid, chlorine, formaldehyde, phosgene, aniline, and hydrogen peroxide are the main non-hydrocarbon chemicals used in the production of primary plastic polymers discussed in this report. While most of these chemicals are used in the production of only one particular polymer, and in this case are defined in their associated subsections in Section 2, methanol and ammonia are used in production of multiple polymers. In this section, we define methanol and ammonia production in more detail.

3.5.1. Methanol production

Methanol is produced traditionally from natural gas in regions other than China, where its production is dominated by coal. Currently, about 55% of global methanol production is based on coal feedstock and about 35% on natural gas, with the rest using coke gas and other

feedstocks such as [220]. In this study, it is assumed that the share of feedstocks other than natural gas, coal, and coke gas is negligible.

With natural gas-based methanol production, natural gas is transformed into syngas with steam and small amounts of CO_2 at a high temperature, with methanol then being synthesized from syngas. With coal-based methanol production, material coal can be produced into methanol after coal gasification, transformation and purification of crude gas, and methanol synthesis [36]. Methanol production from coal has significantly higher energy consumption (~24 GJ/t methanol) compared to methanol from natural gas (~14 GJ/t methanol) [51]. In addition, methanol production has significantly low conversion efficiency, ranging from 67-75% for natural gas to methanol, and 48-61% for coal to methanol [179,221]. Appendix Table A.10 shows the conversion efficiency rates used in this analysis.

3.5.2. Ammonia

Ammonia is consumed for acrylonitrile (for ABS) and formaldehyde (for PU) production in the plastics industry. While most of global ammonia production is based on steam reforming of natural gas, significant quantities are produced by coal gasification [222,223]. In 2020, of the 185 Mt of ammonia produced, 72% relied on natural gas-based steam reforming, 26% on coal gasification, about 1% on oil products, and a fraction of a percentage point on electrolysis [224]. Steam reforming of natural gas requires high amounts of energy usage mainly due to its high operating temperature (in the range of 400-500°C) and pressure (in the range of 15-30 MPa) [224]. The energy demand of the process is in the range of 15.4 to 40 GJ per tonne ammonia [51,224,211]. Approximately 5% of the natural gas produced globally is utilized for ammonia production via this process [224]. In the steam reforming of natural gas, typically more than 60% of the natural gas inputs are used as feedstock [224]. The energy efficiency of coal gasification-based ammonia production is comparatively higher, in the range of 28 to 50 GJ per tonne ammonia, more than half of which is used as feedstock [51,223]. According to IEA [224], the global average energy intensity of ammonia production today is around 41 GJ per tonne on a net basis.

In addition, a global average of about 0.65 kg natural gas per kg ammonia and about 1.5 kg coal per kg ammonia are used as feedstock during ammonia production [225,226].

3.6. Extraction and mining *(of fossil fuels)*

Fossil fuels, namely crude oil, natural gas, and coal, are used as feedstock and fuel energy sources of plastic production. Extraction of fossil fuels includes several activities: from exploration, through drilling, fracking, and mining, and then development, production and extraction, to surface processing and transport to refineries and/or processing facilities. Each of these activities causes emissions: direct emissions, like CH_4 leakage and flaring, along with emissions from fuel combustion [227].

To our knowledge, there is no robust literature discussing the energy intensity of global fossil fuel mining and extraction. There are very few comprehensive datasets covering global emissions from crude oil and natural gas production, and coal mining [e.g., 198,199,228-239]. Emissions related to leakage and venting are highly uncertain, due to both a lack of data and the high variability of operations across supply chains. Literature estimates for the global weighted

GHG emissions for crude oil production range from 7.3-13.3 gCO$_2$e/MJ crude oil [228-233]; for natural gas production range from 7.5-20 gCO$_2$e/MJ natural gas [198,199,233-236]; and for coal production is about 0.2 kg CO$_2$e/kg coal [237-239]. In this analysis, we use

- 10.3 gCO$_2$e/MJ crude oil, (or 0.5 kg CO$_2$e/kg crude oil with an average heat value of 44.5 MJ/kg crude oil for unit GHG emissions of crude oil production [240]),
- 13.3 gCO$_2$e/MJ natural gas, (or 0.7 kg CO$_2$e/kg natural gas with an average heat value of 50 MJ/kg natural gas for unit GHG emissions of natural gas production [240]), and
- 0.2 kg CO$_2$e/kg coal for unit GHG emissions of coal production.

However, we acknowledge that estimation of non-CO$_2$ gases, particularly, CH$_4$ emissions generated during the extraction and mining of fossil fuels, pose a challenge due to uncertainty and variability around exact quantities– as they do for the energy system more broadly [234]. Indeed, more recent literature indicates that greater quantities of CH$_4$ are emitted from fossil fuel extraction and mining processes than previously thought [241].

4. Scenarios

The plastic industry's current growth trajectory is exponential and plastic production is expected to double or triple by 2050 [8]. In this report, we explore the total GHG emissions and carbon budget impact from primary plastic production from 2019 through 2050 under three main business-as-usual (BAU) scenarios based on three sets of plastic production growth assumptions and assuming the power grid remains constant (see Table 15). We do not model plastic production growth, but instead scale our GHG emissions analysis based on a no growth scenario and two different demand growth scenarios from two different sources, namely OECD [3] and NASEM [9] (Figure 23). The OECD outlook provides individual growth trajectories ranging from 2-2.8% per plastic polymer, with an average growth of 2.5% in total plastic demand between 2019 and 2050. Figure A.2 in Appendix A presents the detailed growth projection used in this analysis by plastic polymer type under a 2.5% annual growth scenario. The NASEM report [9] estimates a 4% annual growth in total plastic demand, without any polymer details. In the 4% annual growth scenario, we assume that all types of plastic polymers grow at a rate of 4% per year. These BAU scenarios reflect continuing the current trends in production and recycling, and assume the current primary plastic production technology portfolio, recycling rate (6.3% in 2019), and the global power sector remain unchanged, represented by the average global grid CO$_2$ emission intensity, during the modeling period. Although renewable power generation capacity has grown rapidly globally in recent years and there are national renewable power generation targets and policies, there are still uncertainties surrounding the actual pace of power sector decarbonization [235]. However, to assess the potential impact of electric grid decarbonization, in which global electricity grid gets decarbonized in response to power sector policies and targets, three additional sensitivity scenarios showing BAU with a decarbonized power grid were used (see Table 15). Table A.12 and Figure A.3 in Appendix display all the emission factors used in this analysis. It is also important to note that the grid CO$_2$ emission intensity that we use in our analysis represents global electricity generation, and could differ from the ones used in the regional analyses.

These scenarios do not necessarily present likely projections; instead, they are designed to demonstrate the potential GHG emissions impact of primary plastic production if the current

production structure and consumption trends stay unchanged. We also do not evaluate the broader portfolio of clean technologies and their potential impact on future emissions from plastic production; rather, we provide a picture of the magnitude of the climate problem if current plastic production and consumption trends remains unchanged.

This analysis also assumes that production equals demand. However, we acknowledge that there may be excess production (supply). In this case, GHG emissions and carbon budget estimates by 2050 would be higher.
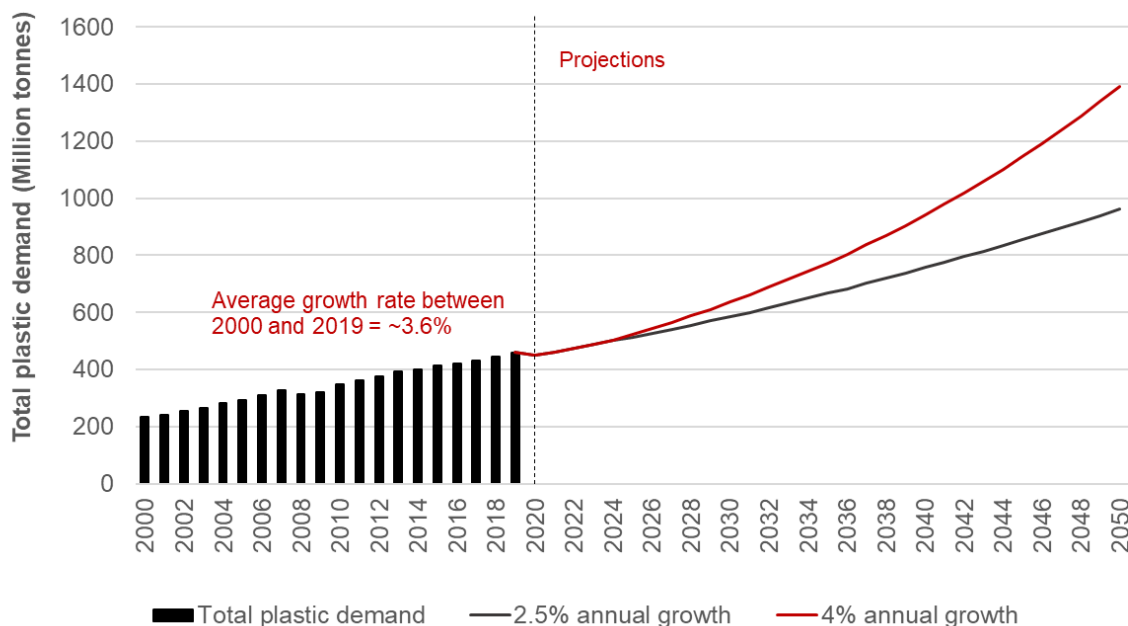
Figure 23. Projections for plastic demand growth.

Note: 2.5% and 4% annual growth projections are based on OECD [3] and NASEM [9], respectively, and represent the total global plastic demand growth.

Table 15. BAU scenarios used in this report

	Annual production growth [1]	Global CO$_2$ emission intensity of electricity generation [2]
BAU with constant power grid scenarios:		
BAU: No growth	No growth	Constant at current levels between 2022 and 2050
BAU: 2.5% growth	2.5% per year	
BAU: 4% growth	4% per year	
BAU with decarbonized power grid scenarios:		
BAU with decarbonized grid: No growth	No growth	Decarbonized grid between 2022 and 2050 in response to stated power sector-specific policies and targets
BAU with decarbonized grid: 2.5% growth	2.5% per year	
BAU with decarbonized grid: 4% growth	4% per year	

5. Results

This section investigates the global climate impact of primary plastic production in the base year (2019) and in the long term between 2019 and 2050. The results are presented as global total and polymer-specific GHG emissions.

5.1. Global GHG emissions from primary plastic production

Our estimates show that GHG emissions from plastic production (from extraction of fossil fuels to shaping of the final product) could amount to the equivalent of 2.24 gigatonnes of carbon dioxide equivalent (GtCO$_2$e) in 2019, representing 5.3% of total global GHG emissions (excluding agriculture and land use, land-use change and forestry (LULUCF)).[19] In comparison, the global aviation sector generated 0.6 gigatonnes of carbon dioxide (GtCO$_2$) of CO$_2$ emissions in 2019, while the global transport sector, including aviation, generated a total of 8.3 GtCO$_2$ in 2019 [243]. By polymer type, approximately 22%, 21%, and 15% of emissions related to plastic production in 2019 come from all PEs together, PET, and PP, respectively (Figure 24). Other key plastics, i.e., PVC, PS, SAN, ABS, and PU are together responsible for around 23% of global emissions from plastic production. This result is based on global production volumes and differentiated emission intensities of specific processes included in the production value chain for each of the nine major plastic types. For example, PE and PP are produced in higher volumes globally, at 109.9 Mt and 78.8 Mt in 2019 respectively, compared with 74.8 Mt of PET. However, they are significantly less emissions intensive on a tonne-for-tonne basis (Figure 24). The results show that the global average weighted emission intensity of nine primary plastic polymer products ranges between 4.5 and 6.5 tonnes of carbon dioxide equivalent/metric tonne (tCO$_2$e/t) with the current production structure (Figure 24). GHG emission intensity of "Other plastics" are assumed as the weighted average of nine primary plastic polymers analyzed in this report.

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[19] Global GHG emissions (excl., agriculture and land use change) was 42.4 GtCO$_2$e in 2019 [244].
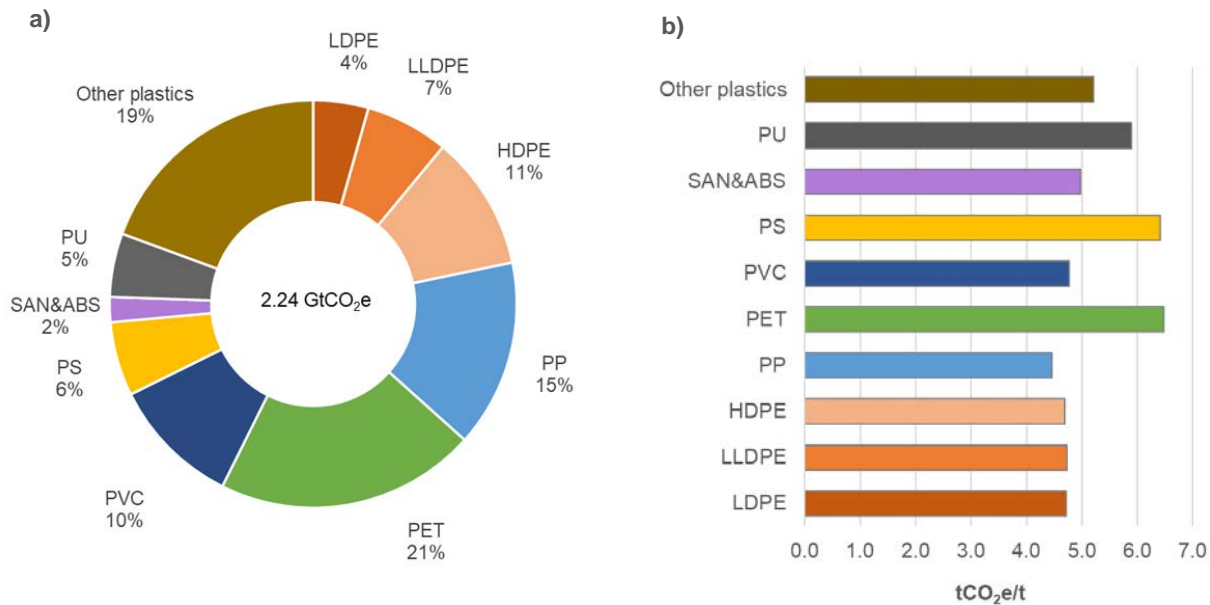
Figure 24. a) GHG emissions from primary plastic production by polymer type in 2019, b) GHG emission intensity of primary plastic polymers by polymer type.

Notes: GHG emission intensities in the figure represent the global weighted production average for primary plastic polymer products and do not represent emission intensity from a particular production pathway, such as PP production via propylene from steam cracking route versus FCC route. GHG emission intensity of "Other plastics" are assumed as the weighted average of nine key polymers analyzed in this study.

Another important aspect is the contribution of production stages to total GHG emissions from primary plastic production. The results show that most (~75%) emissions from plastic production occur from the steps prior to polymerization (Figure 25). Emissions stem primarily from the production of monomers, hydrocarbons, and non-hydrocarbon chemicals. More than a quarter (26%) of emissions are generated during monomer making (e.g., ethylene, propylene, purified terephthalic acid (PTA), vinyl chloride monomer (VCM), and styrene). Slightly more (29%) are generated from the refining of hydrocarbons (e.g., naphtha, ethane, toluene, and p-xylene) and production of other non-hydrocarbon chemicals (e.g., methanol, ammonia, and chlorine), while 20% of emissions come from the extraction of fossil fuels needed for feedstock and process energy demand of plastic production. The remaining 25% is generated from the polymerization and product-shaping stages together.

Primary plastic production

20% of GHG emissions	16% of GHG emissions	13% of GHG emissions	26% of GHG emissions	8% of GHG emissions	17% of GHG emissions
Extraction and/or mining *(of fossil fuels)*	Hydrocarbon refining and processing	Other chemicals production *(non-hydrocarbon)*	Monomer production	Polymerization	Product shaping
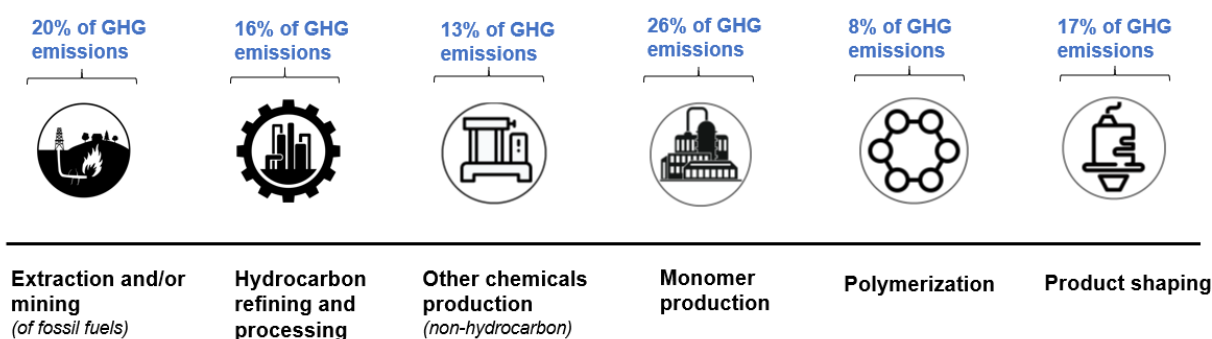
Figure 25. GHG emissions shares of plastic production stages in 2019.

Figure 26 compares the GHG emissions from iron and steel and cement sectors with primary plastic production. In general, GHG emissions reported from industrial sectors do not include emissions related to the extraction and mining of raw materials (e.g. iron and limestone), as well as the casting or shaping of crude materials into finished products. GHG emissions from the mining and quarrying sector and manufacturing sector are accounted separately. Therefore, we are discounting the GHG emissions related to "extraction and/or mining" and "product shaping" when comparing primary plastic production to iron and steel and cement sectors in Figure 26. As can be seen, production of primary plastics generated about 54% and 62% of the emissions from iron and steel and cement, respectively, in 2019.
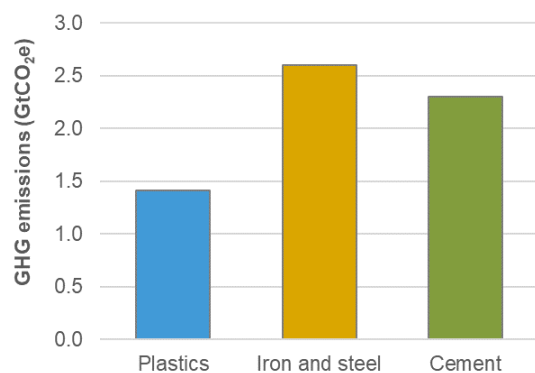
Figure 26. GHG emissions from global production of primary plastics, compared to global production of iron and steel and cement sectors.

Notes: Emissions related to iron and steel and cement sectors are from IEA [245,246].

Figure 27 shows our estimates of GHG emissions from global plastic between 2019 and 2050 under the three main BAU scenarios with a constant power grid. GHG emissions from primary plastic production could more than double by 2050, to 4.75 $GtCO_2e$ under the growth scenario of 2.5%/yr; or almost triple by 2050, to 6.78 $GtCO_2e$ under the growth scenario of 4%/yr. Under these two growth scenarios, cumulative GHG emissions from primary plastic production could amount to 106-126.6 $GtCO_2e$ between 2019 and 2050, equivalent to 21-25% of the remaining carbon budget that offers a 50% chance of staying below the 1.5°C threshold (Table 16). Plastics' share of the carbon budget increases to 26-31% when considering a smaller carbon

budget that offers a 67% chance of staying below the 1.5°C threshold. If production levels remained constant from 2025 onward (i.e., No growth), primary plastic production would still account for 15% and 19% of these carbon budgets, respectively.

Under the BAU scenarios with decarbonized electric grid, GHG emissions drop to about 3.59 GtCO₂e and 5.13 GtCO₂e in 2050 under 2.5%/yr and 4%/yr plastic production growth, respectively (Figure 28). While the decarbonized grid results in 25% less GHG emissions in 2050, GHG emissions from primary plastic production remain high. Nonetheless, cumulative GHG emissions from plastic production could still account for 17-21% and 22-26% of the remaining carbon budget that offers a 50% and 67% chance of staying below the 1.5°C threshold, respectively (Table 16). In addition, under a constant plastic production (i.e., No growth) scenario with decarbonized grid, plastic production could still account for 13% and 16% of these carbon budgets, respectively.
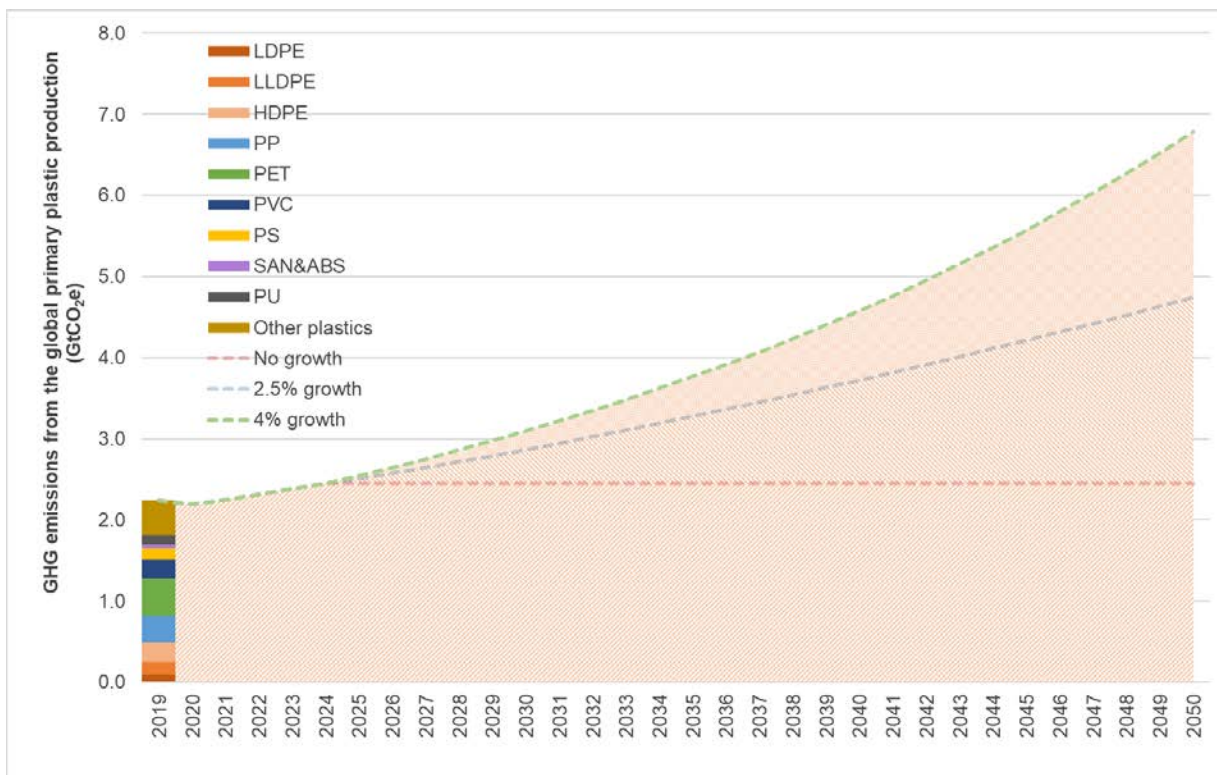
Figure 27. GHG emissions from global primary plastic production between 2019 and 2050 under BAU No growth, 2.5% growth, and 4% growth scenarios.

Notes: The figure represents the results under BAU with constant power grid scenarios.
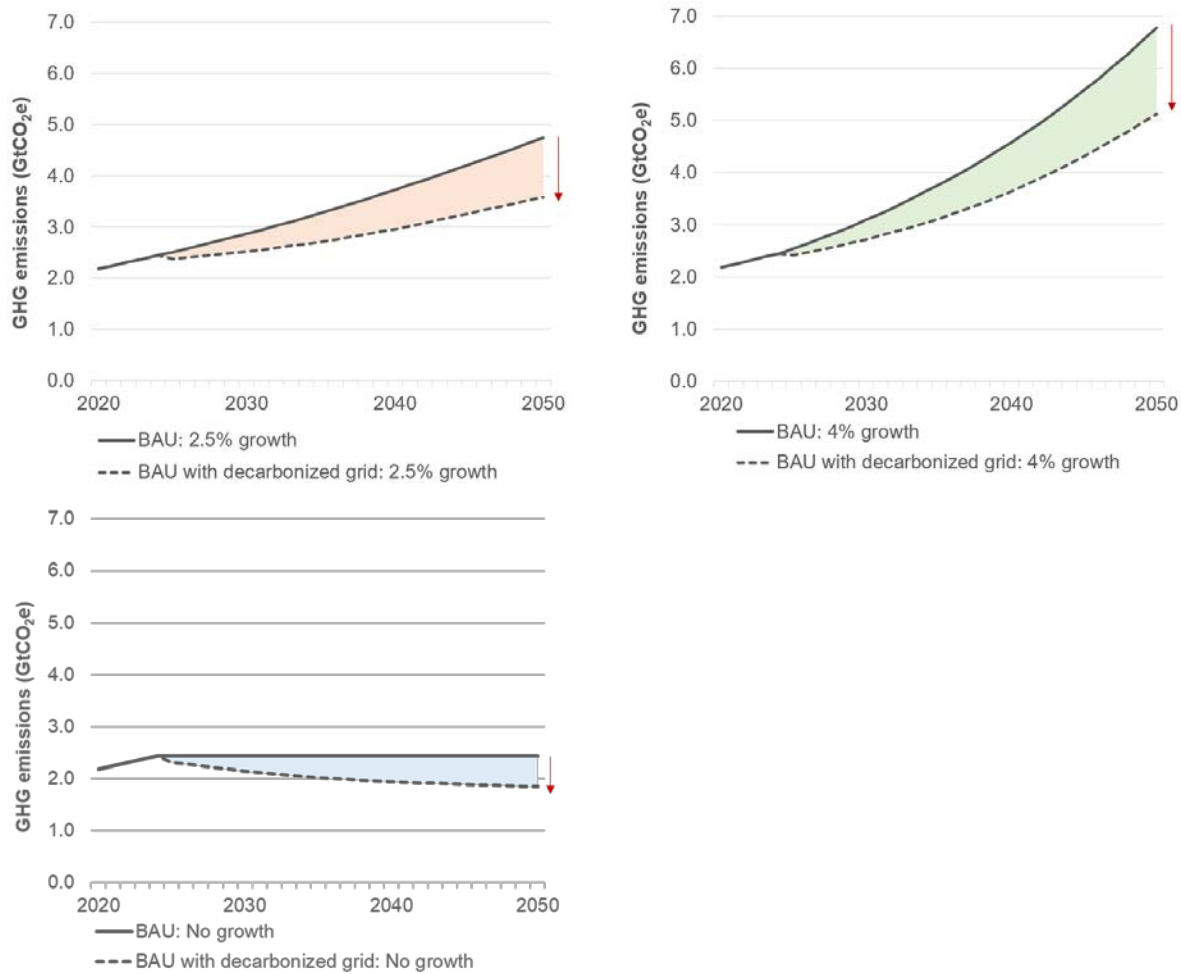
Figure 28. GHG emissions from global primary plastic production between 2019-2050 under BAU with decarbonized grid scenarios, compared to BAU with constant power grid scenarios.

Note: Please see Table A.12 and Figure A.3 for the global average electricity grid CO_2 emission intensity used in this analysis.

Table 16. Cumulative GHG emissions from global primary plastic production and associated carbon budget impact by 2050 under No growth, 2.5% growth, and 4% growth scenarios.

	Cumulative GHG emissions between 2019 and 2050 (GtCO$_2$e)	50% chance of staying below the 1.5°C temperature increase by 2050	67% chance of staying below the 1.5°C temperature increase by 2050
BAU with constant power grid through 2050			
BAU: No growth	77.4	15%	19%
BAU: 2.5% growth	106.0	21%	26%
BAU: 4% growth	126.6	25%	31%
BAU with decarbonized power grid through 2050			
BAU with decarbonized grid: No growth	66.1	13%	16%

BAU with decarbonized grid: 2.5% growth	88.7	17%	22%
BAU with decarbonized grid: 4% growth	105.0	21%	26%

Notes: Current central estimate of the remaining carbon budget from 2020 onwards for limiting warming to 1.5°C by 2050 with a probability of 50% has been assessed as 500 GtCO2e, and for limiting warming to 1.5°C by 2050 with a probability of 67% has been assessed as 400 GtCO2e [2]. In the table, carbon budget shares are estimated to with the cumulative emission from global primary plastic production between 2020 and 2050.

In addition, plastic production currently relies heavily on crude oil, natural gas, and/or coal for both feedstock and process energy demand. Our estimates indicate that global primary plastic production accounted for around 527 Mtoe, or 12% of global demand for oil, and around 237 bcm, or 8.5% of global demand for natural gas. Most of this fossil fuel input is consumed as feedstock, representing 9.1% of global oil demand, and 5.2% of global natural gas demand.[20] IEA [247] estimates that petrochemical feedstocks, including plastics and non-plastic products, account for 14% of global oil demand. In addition, according to Michaux [248], global oil demand of plastic production for feedstock was approximately 10% in 2018, while according to analysis by Statista [249], it was about 10% in 2019.[21] While we are not sure what materials and processes are included in IEA's, Michaux's, and Statista's analyses, both are in close proximity to our crude oil result.

Table 17 provides a comparison of our estimates with the previous studies in the literature with a similar scope. Our GHG emission estimates in 2019 are significantly higher than previous estimates due to the increased level of granularity in modeling production processes, technologies, and routes. We also have no "by-product" assumption. Our modeling allocates its share of emissions to each product based on mass allocation, as discussed in Sections 2 and 3. Please also note that most previous literature of similar scope also includes GHG emissions associated with recycled plastic products in total GHG emission levels.

Table 17. Comparative analysis of the GHG emissions from the global plastic production in different studies with similar scope.

Reference	GHG Emissions from plastic production (GtCO2e)
This study	2.24 GtCO2e in 2019; 4.75-6.78 GtCO2e in 2050 (under a 2.5-4% demand growth between 2019 and 2050)
OECD [3]	1.8 Gt CO2e in 2019 to 4.3 Gt CO2e in 2060 (under a 2.5% demand growth between 2019 and 2050, includes recycling)
Zheng and Suh [17]	~1.6 GtCO2e in 2015; 5.9 GtCO2e in 2050 (under a 4% demand growth between 2015 and 2050, includes recycling)
Cabernard et al. [18]	1.9 GtCO2e in 2015 (includes a captive power modeling, includes recycling)

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[20] Please note that fossil fuel input calculations (1) are based on final energy consumption and do not include fossil fuels combusted for electricity generation, (2) do not cover fossil fuels consumed during the extraction and mining stage. GHG emissions from the "extraction and mining" stage is based on global GHG emissions intensity, not energy intensity. Please refer to Section 3.6 for modeling of the "extraction and/or mining" stage.

[21] Statista analysis estimates 9 million barrel per day (1.26 Mtoe per day) oil demand for plastics production globally [249]. We assume that production continues every day of the year (365 days).

| CIEL [19] | 0.86 Gt CO$_2$e in 2019; 2.8 GtCO$_2$e in 2050 |

Notes: Please note that Zheng and Suh [17] and Cabernard et al. [18] estimate GHG emissions in 2015 and OECD [3] and CIEL [19] provide GHG emission estimates for 2019. Please also note that this table does not include references such as Stegmann et al. [5], GRID-Arendal [20], Vidal et al. [21], and Meng et al. [22], which based their discussions of GHG emissions to the citations already listed in Table 15.

We describe the primary plastic production system in detail to estimate GHG emission levels from primary plastic production. However, some parameters may have higher uncertainty and variability. Table 18 summarizes results from our sensitivity analysis. The results have the highest sensitivity to the share of MTO-based olefins production, due to the high energy intensity of methanol production, particularly via coal-based production (which accounts for about 55% of current global methanol production). On the other hand, the sensitivity of the results to the GHG emission factors used in the extraction of fossil fuels is low. While sensitivity analysis provides insights into their impact on results, these factors can be further explored in future analyzes with more detailed results.

Table 18. Sensitivity of results to key parameters, GHG emissions from the global primary plastic production.

Parameter in BAU	Change in parameter	GHG Emissions	GHG Emissions (% Change)
Global average GHG emission for crude oil extraction - 10.3 gCO$_2$eq/MJ	7.3 gCO$_2$eq/MJ	2.16 GtCO$_2$e	-3.6%
	13.3 gCO$_2$eq/MJ	2.32 GtCO$_2$e	3.6%
Global average GHG emission for natural gas extraction - 13.3 gCO$_2$eq/MJ	7.5 gCO$_2$eq/MJ	2.17 GtCO$_2$e	-3.1%
	20 gCO$_2$eq/MJ	2.32 GtCO$_2$e	3.6%
Energy consumption for steam cracking processes	The lowest end of the range for each steam cracking process	2.18 GtCO$_2$e	-2.8%
	The highest end of the range for each steam cracking	2.33 GtCO$_2$e	4.0%
MTO global production share in ethylene production - 3.5%	0%	2.1 GtCO$_2$e	-6.3%
	10%	2.6 GtCO$_2$e	16.0%
Global share of natural gas-based methanol production - 35%	100%	2.13 GtCO$_2$e	-5.0%
Global share of coal-based methanol production - 55%	100%	2.34 GtCO$_2$e	4.5%
Energy consumption for polymerization	The lowest end of the range for each polymer's polymerization process	2.2 GtCO$_2$e	-1.8%
	The highest end of the range for each polymer's polymerization process	2.32 GtCO$_2$e	3.6%

Please see Appendix A for a comparison of our estimates of process energy consumption for primary plastic production with selected studies in the literature.

5.2. Detailed GHG emission results for individual polymers

Figure 29 provides detailed GHG emission results for each polymer type analyzed in this study within the scope of BAU with constant power grid scenarios. As can be seen from the figure, emission contribution of production stages differs per polymer.
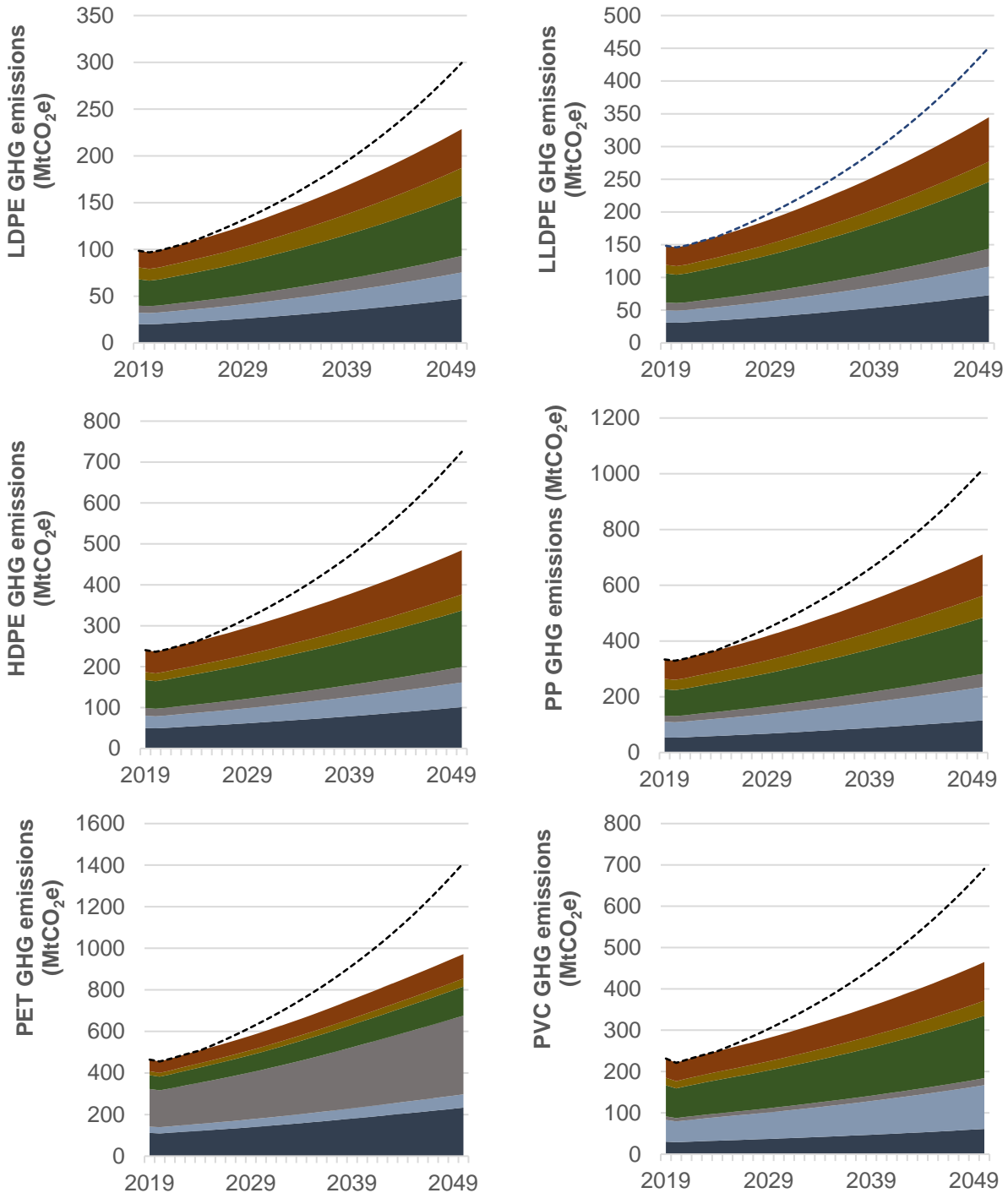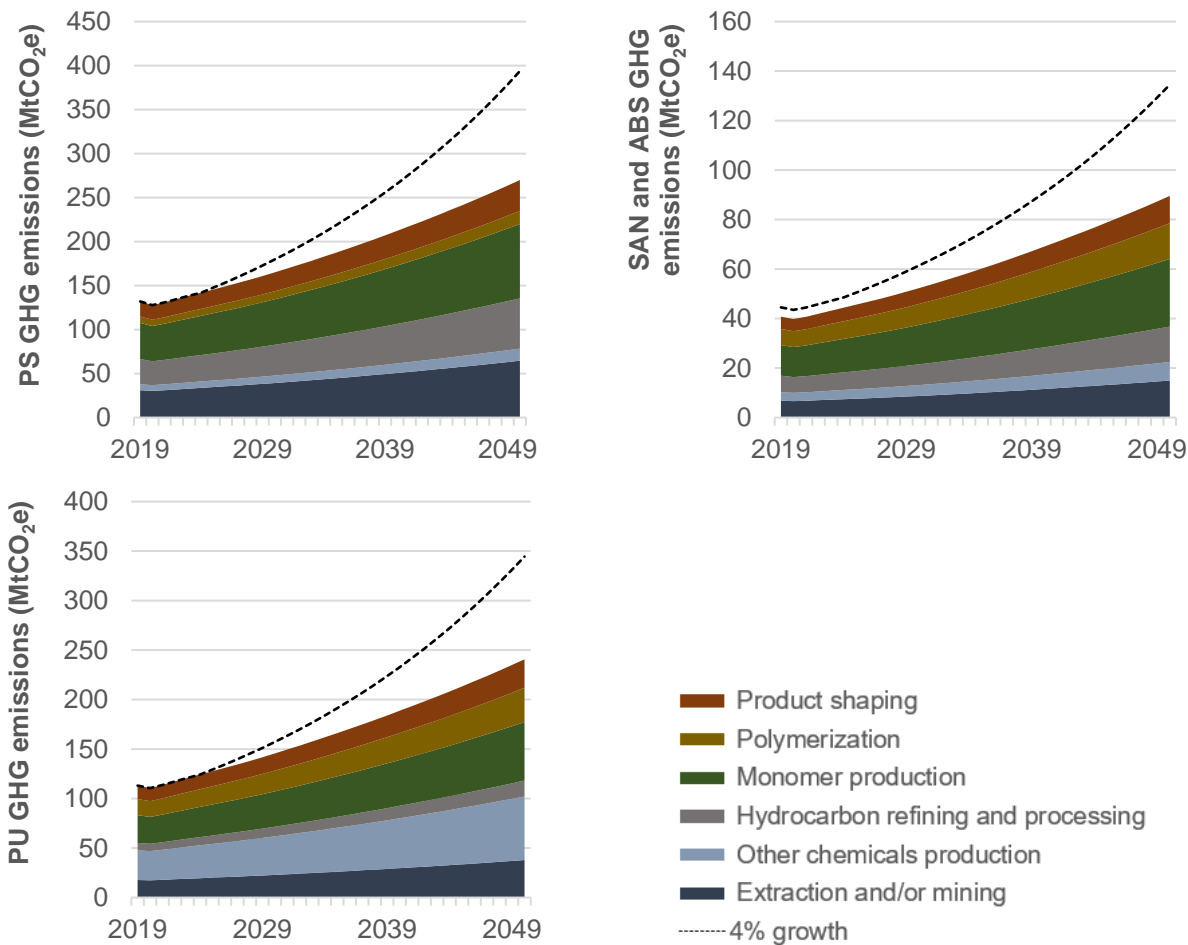
Figure 29. GHG emissions from LDPE, LLDPE, HDPE, PP, PET, PVC, PS, SAN&ABS, and PU production between 2020 and 2050 with production stage details.

Notes: Colored shaded areas in the charts represent production stages under the 2.5% growth scenario. Dotted line in the charts represents total GHG emissions under the 4% growth scenario. Please note that the scale on the y-axis is different for each polymer.

The production of LDPE, LLDPE and HDPE primary plastic polymer products results in emissions of approximately 98.5 MtCO$_2$e, 148.3 MtCO$_2$e and 240.4 MtCO$_2$e in 2019; 69-72% of emissions come from pre-polymerization stages (Figure 29). The monomer production stage has the highest share for all three PE polymers. GHG emissions from LDPE, LLDPE and HDPE production could reach to 228.6 MtCO$_2$e, 344.8 MtCO$_2$e and 484.5 MtCO$_2$e under the growth scenario of 2.5%/yr; and to 299.4 MtCO$_2$e, 451.5 MtCO$_2$e and 725.4 MtCO$_2$e under the growth scenario of 4%/yr. Individually, polymerization, steam cracking of naphtha and ethane, methanol production, crude oil and natural gas productions contributes the most for each PE polymer (Figure 30-32). As can be seen, the ethane-based steam cracking process has a smaller emission impact compared to the naphtha-based steam cracking process. However, the contribution of ethane production in natural gas processing facilities and the extraction of natural gas used as raw materials (for ethane) is much higher than the production of naphtha and crude oil. Ethane-based PE production produces more GHG emissions than naphtha-based production when the entire production value chain is considered. Methanol production also has a significantly high GHG emissions footprint for all three PEs. Methanol is used by MTO for ethylene production

and has a very high energy intensity, particularly through coal-based production (this is approximately 55% of the current global production of methanol). In addition, although film extrusion has relatively low energy consumption compared to other product shaping processes, it generates a higher emission footprint for LDPE and LLDPE. This is due to its larger production share (70% of LDPE and LLDPE production was from film extrusion in 2019). Rotational molding, on the other hand, has a significantly higher production energy intensity, increasing the contribution of this process to LLDPE emissions. Due to the more balanced share of production methods, there is no single product shaping process that provides the highest emissions in HDPE (unlike LDPE and LLDPE).

Appendix Table A.12-14 provides more detail about LDPE, LLDPE, and HDPE production process output volumes, energy consumption, and GHG emissions.

Figure 30. Breakdown of GHG emissions associated with global LDPE production in 2019.

Notes: SC = Steam cracking, MTO = Methanol-to-olefin.
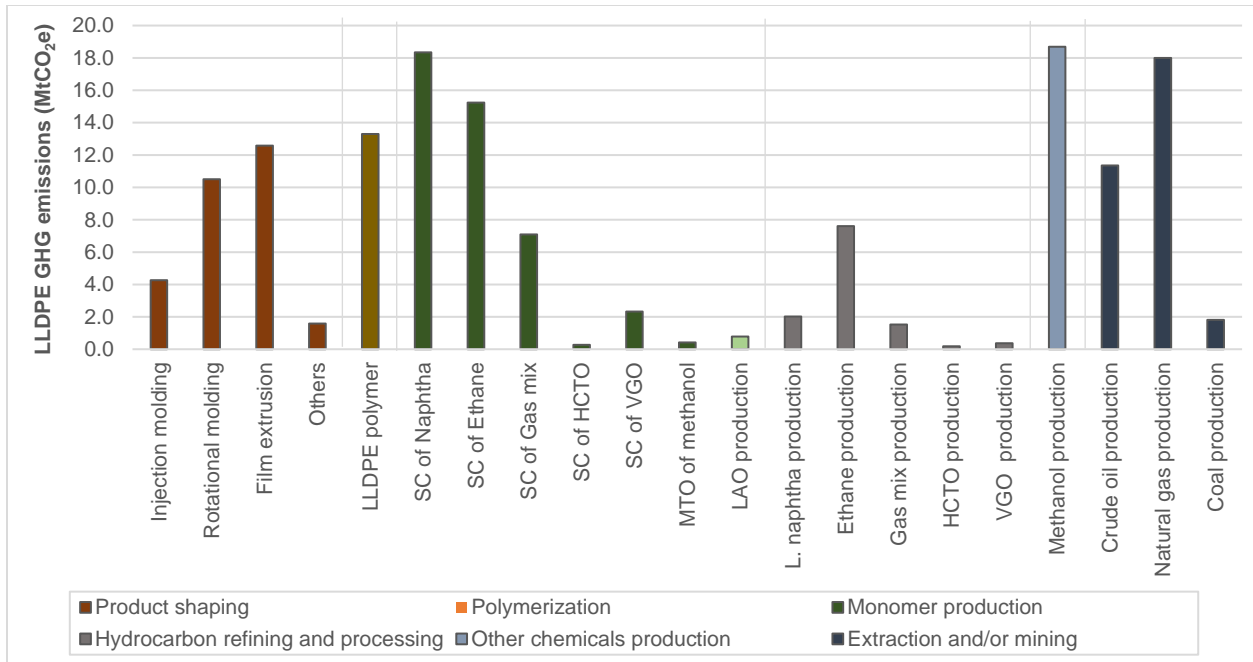
Figure 31. Breakdown of GHG emissions associated with global LLDPE production in 2019.

Notes: SC = Steam cracking, MTO = Methanol-to-olefin.
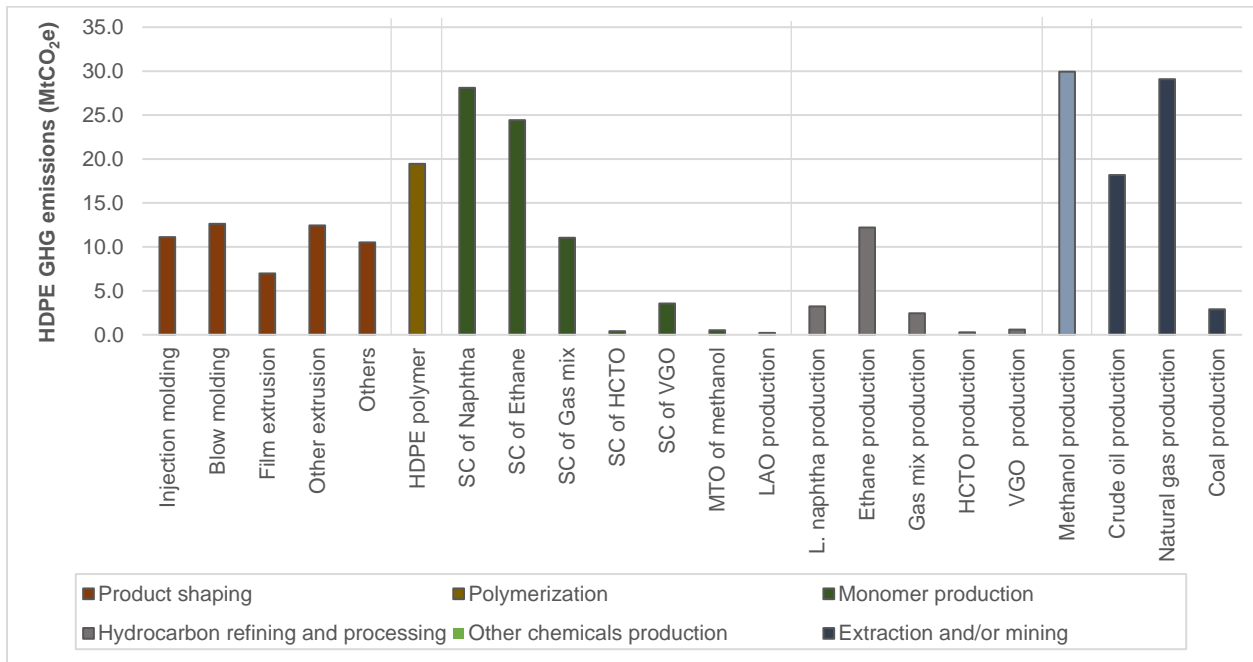
Figure 32. Breakdown of GHG emissions associated with global HDPE production in 2019.

Notes: SC = Steam cracking, MTO = Methanol-to-olefin.

The production of PP primary plastic polymer products results in approximately 333.9 MtCO$_2$e in 2019 with 68% coming from stages before polymerization (Figure 29). The monomer production stage has the highest share as in PE polymer products. GHG emissions from PP

production could reach to 710.1 MtCO2e under the growth scenario of 2.5%/yr; and to 1,014.8 MtCO2e under the growth scenario of 4%/yr. Figure 33 provides a detailed picture of contribution of different processes to the GHG emissions from PP production. Monomer (propylene) production produces the most GH emissions (~28%) in the production process. As can be seen, propylene production from steam cracking (referred to as "SC" in Figure 33) makes a much higher contribution to compared to other propylene production processes. A major contributing factor is the higher energy intensity of steam cracking processes compared to other processes. Steam cracking also has the highest share (~43%) of global propylene production (see Section 3.3). In comparison, FCC has ~38% of global propylene production with much lower production energy intensity. As can be seen in Table 19, although the production shares of propylene from the steam cracking (~43%) and FCC (~38%) processes assumed in this analysis are similar, emissions from SC are almost twice that of FCC. However, FCC uses crude oil as the feedstock for propylene, which increases demand for crude oil and, in turn, GHG emissions from extraction of crude oil (compared to natural gas). As in PE production, methanol production also has a significantly high GHG emissions footprint in PP production. Methanol is used by MTO and MTP for propylene production (~5% of total global production).

Appendix Table A.15 provides more details about PP production process output volumes, energy consumption, and GHG emissions.
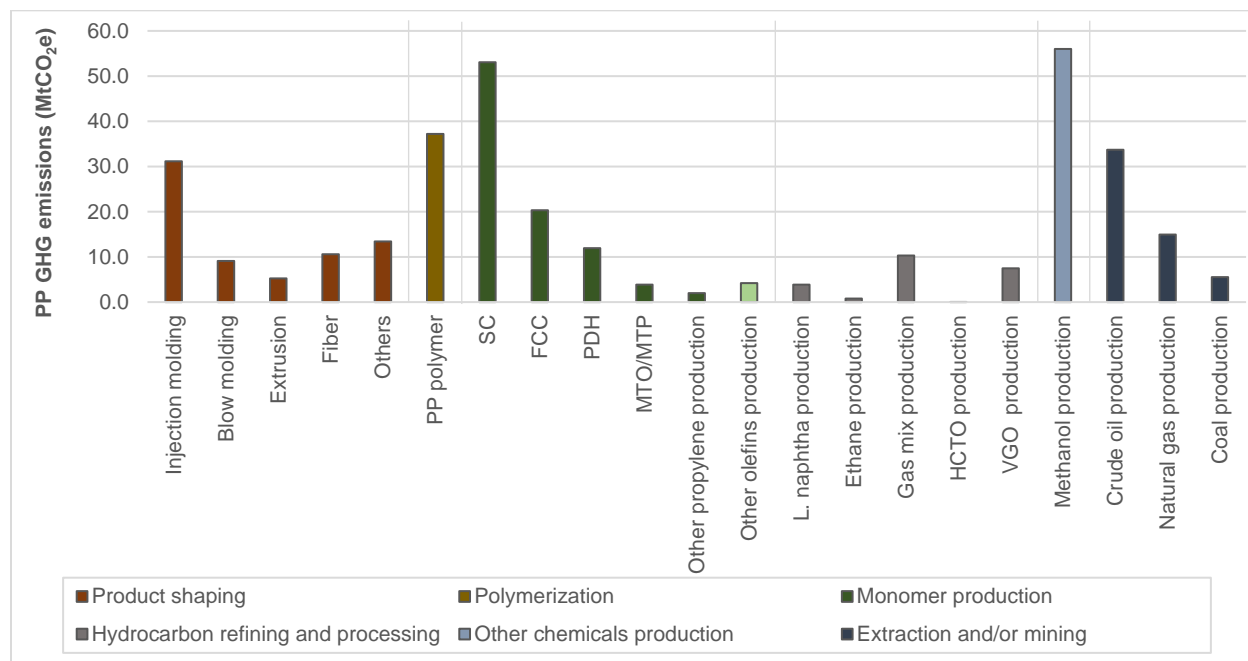
Figure 33. Breakdown of GHG emissions associated with global PP production in 2019.

Notes: SC = Steam cracking, MTO = Methanol-to-olefin, MTP = Methanol-to-propylene.

Table 19. Total GHG emissions from propylene production per production route in 2019

	GHG emissions (MtCO2e)		GHG emissions (MtCO2e)
SC route	**78.5**	**FCC route**	**40.5**
Monomer production	53.1	Monomer production	20.3

Hydrocarbon refining and processing	9.4	Hydrocarbon refining and processing	6.8
Extraction and/or mining	15.9	Extraction and/or mining	13.4
PDH route	**22.6**	**MTO/MTP route**	**39.7**
Monomer production	11.9	Monomer production	3.9
Hydrocarbon refining and processing	5.2	Other chemicals production	18.0
Extraction and/or mining	5.5	Extraction and/or mining	17.9
"Others" route	**8.5**		
Monomer production	6.2		
Hydrocarbon refining and processing	1.1		
Extraction and/or mining	1.3		

Notes: Others include Metathesis and Superflex. SC = Steam cracking, FCC = Fluid catalytic cracking, PDH = Propane dehydrogenation, MTO = Methanol-to-olefin, MTP = Methanol-to-propylene.

The production of PET primary plastic polymer products results in approximately 464.5 $MtCO_2e$ in 2019, of which 84% comes from pre-polymerization stages (Figure 29). GHG emissions from PET production could reach to 971.8 $MtCO_2e$ under the growth scenario of 2.5%/yr; and to 1,410.3 $MtCO_2e$ under the growth scenario of 4%/yr. The hydrocarbon production stage has the highest share. Figure 34 provides a detailed picture of contribution of different processes to the GHG emissions from PET production. As can be seen, pygas and p-xylene production are two of highest contributors to GHG emissions from PET production. While the production shares vary largely, all production technologies commonly used for p-xylene production are very energy intensive (14.1-27.3 GJ/tonne p-xylene) (see Section 3.4.2). Pygas is used to produce p-xylene (4% of global p-xylene production) in addition to toluene, which is then used to produce p-xylene through toluene-based production processes such as transalkylation and disproportionation of toluene (17% of global p-xylene production). Although the pygas cut (i.e. pyrolytic cracking) of p-xylene and toluene is not high (4% for p-xylene and 25% for toluene - see Section 3.4.2 for details), pygas is produced by steam cracking of naphtha and VGO (steam cracking is a very energy and emission intensive production). In addition, more than 70% p-xylene and toluene are produced by catalytic reforming of naphtha. The heavy dependence of naphtha in PET production leads to high demand for crude oil (as the feedstock for both light and heavy naphtha production) and the emissions associated with its extraction.

Appendix Table A.16 provides more details on PET production process output volumes, energy consumption, and GHG emissions.

Figure 34. Breakdown of GHG emissions associated with global PET production in 2019

The production of PVC primary plastic polymer products results in approximately 231.4 MtCO$_2$e in 2019, 72% of which comes from stages before polymerization (Figure 29). GHG emissions from PVC production could reach to 465 MtCO$_2$e under the growth scenario of 2.5%/yr; and to 690.4 MtCO$_2$e under the growth scenario of 4%/yr. The monomer production stage has the highest share of emissions, followed by other chemicals production. As can be seen in Figure 35, the largest contributors to GHG emissions from PVC production are VCM (monomer), ethylene (monomer), and chlorine (other chemicals) productions. Chlorine production is a very energy-intensive process, and all three production technologies used in this analysis for chlorine production have similar energy intensities (9.3-13.3 GJ/tonne chlorine) (see Section 2.4). VCM production (including EDC production) is also an energy- and GHG emission-intensive process. Like other polymers, ethylene comes from steam cracking and methanol-based MTO processes, both of which are highly energy- and GHG emission-intensive. In addition, pipes and fittings have a higher emission footprint compared to other product-shaping processes due to their higher production share (45% in 2019).

Appendix Table A.17 provides more details on PVC production process output volumes, energy consumption, and GHG emissions.

Figure 35. Breakdown of GHG emissions associated with global PVC production in 2019.

Notes: VCM production includes EDC production.

The production of PS primary plastic polymer products results in approximately 131.9 MtCO2e in 2019, of which 82% comes from pre-polymerization stages (Figure 29). GHG emissions from PS production could reach to 270 MtCO2e under the growth scenario of 2.5%/yr; and to 393.8 MtCO2e under the growth scenario of 4%/yr. The monomer production stage has the highest share of emissions, followed by hydrocarbon production. Figure 36 provides a detailed picture of contribution of different processes to the GHG emissions from PS production. As can be seen, the production of almost all monomers (i..e, styrene, ethylene, benzene, and butadiene) except butadiene has a high contribution GHG emissions resulting from PS production. Butadiene is used in very small amounts for HIPS production (see Section 2.5). Pygas is the highest contributors to GHG emissions from PS production. First of all, pygas is used to produce styrene, although the production share is relatively small (less than 15% of global styrene production) compared to dehydrogenation of ethylbenzene. Pygas is also used to produce benzene (25% of global benzene production) in addition to toluene, which is then used to produce benzene through toluene-based production processes such as transalkylation and disproportionation of toluene (25% of global p-xylene production) (see Section 3.4.2 for details). Pygas is produced by steam cracking of naphtha and VGO. Steam cracking is a very energy- and GHG emission-intensive production. In addition, 50% benzene is produced by catalytic reforming of naphtha. Like PET, the heavy dependence of naphtha and VGO in PS production leads to high demand for crude oil (as the feedstock for both light and heavy naphtha production) and the emissions associated with its extraction.

Appendix Table A.18 provides more details about PS production process output volumes, energy consumption, and GHG emissions.
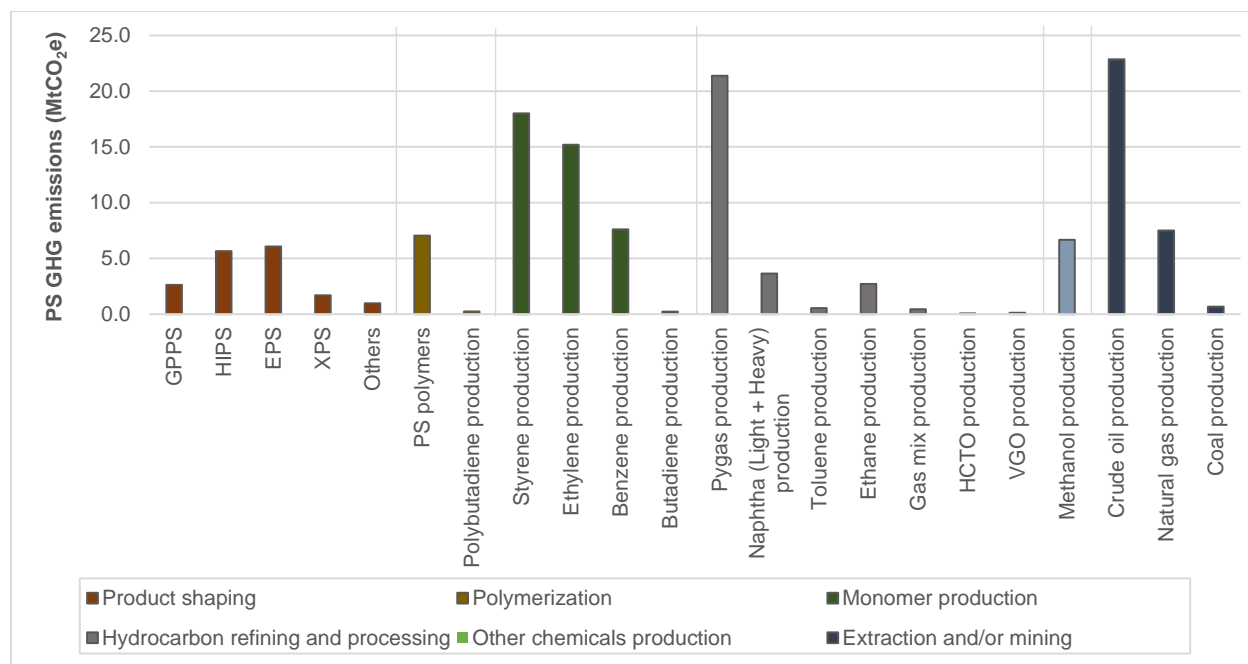
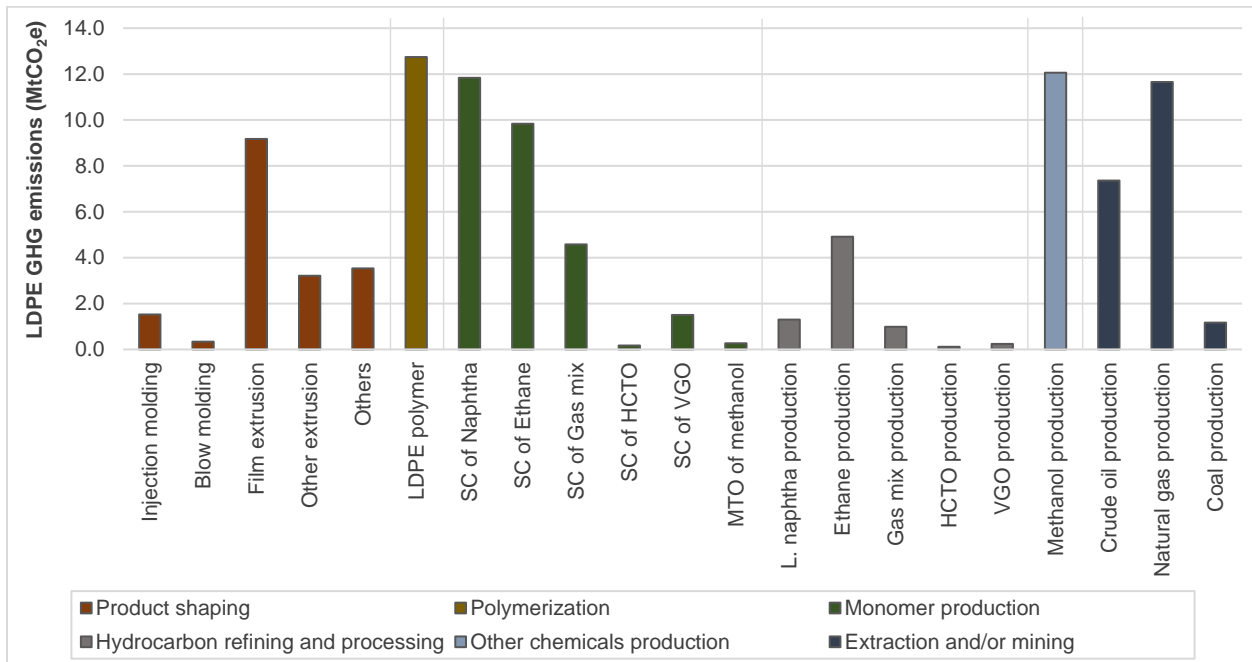*Figure 36. Breakdown of GHG emissions associated with global PS production in 2019.*

The production of SAN and ABS primary plastic polymer products results in approximately 44.5 MtCO₂e in 2019, of which 74% comes from pre-polymerization stages (Figure 29). GHG emissions from SAN and ABS production could reach to 98 MtCO₂e under the growth scenario of 2.5%/yr; and to 134.5 MtCO₂e under the growth scenario of 4%/yr. The monomer production stage has the highest share of emissions. Figure 37 provides a detailed picture of contribution of different processes to the GHG emissions from SAN and ABS production. As can be seen, the production of almost all monomers (i..e, styrene, ethylene, benzene, and butadiene) and pygas has a high contribution GHG emissions resulting from SAN and ABS production. Pygas is used to produce styrene, although the production share is relatively small (less than 15% of global styrene production) compared to dehydrogenation of ethylbenzene. Pygas is also used to produce benzene (25% of global benzene production) in addition to toluene, which is then used to produce benzene through toluene-based production processes such as transalkylation and disproportionation of toluene (25% of global p-xylene production) (see Section 3.4.2 for details). Pygas is produced by steam cracking of naphtha and VGO. Steam cracking is a very energy- and GHG emission-intensive production. In addition, 50% benzene is produced by catalytic reforming of naphtha. Like PET and PS, the heavy dependence of naphtha and other crude oil-based products in SAN and ABS production leads to high demand for crude oil (as the feedstock for both light and heavy naphtha production) and the emissions associated with its extraction. Butadiene is used in ABS production, and it is a product of energy- and GHG emission-intensive steam cracking of naphtha, gas mix, and VGO.

Appendix Table A.19 provides more details about SAN and ABS production process output volumes, energy consumption, and GHG emissions.
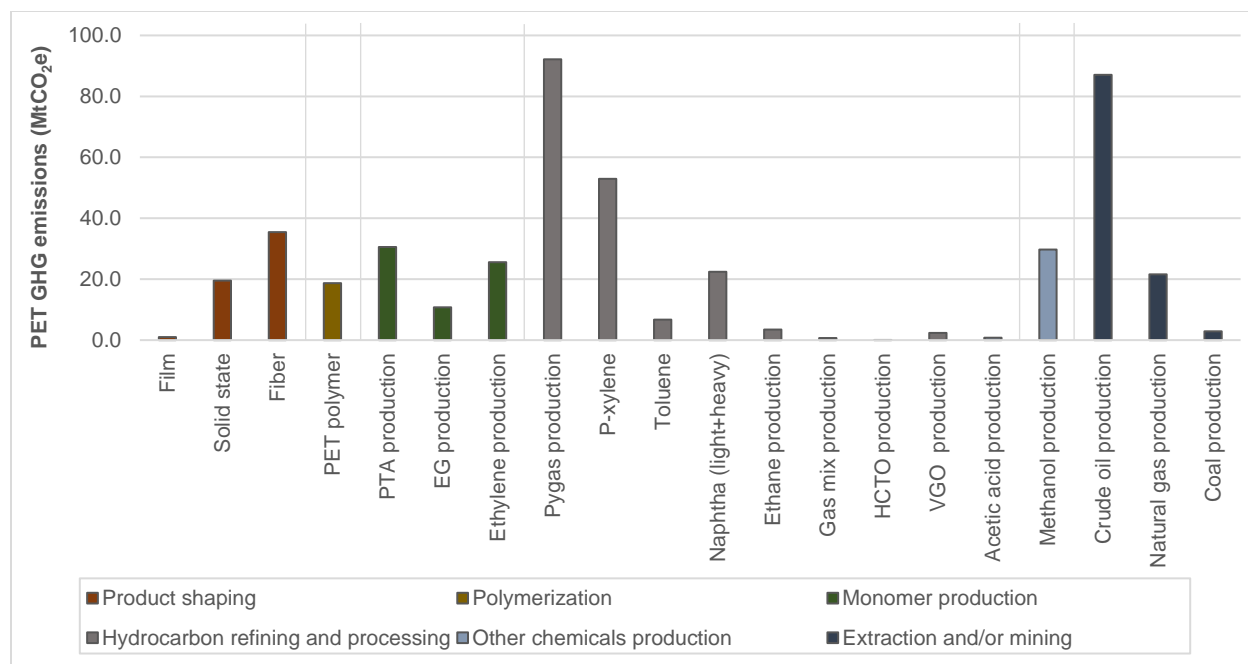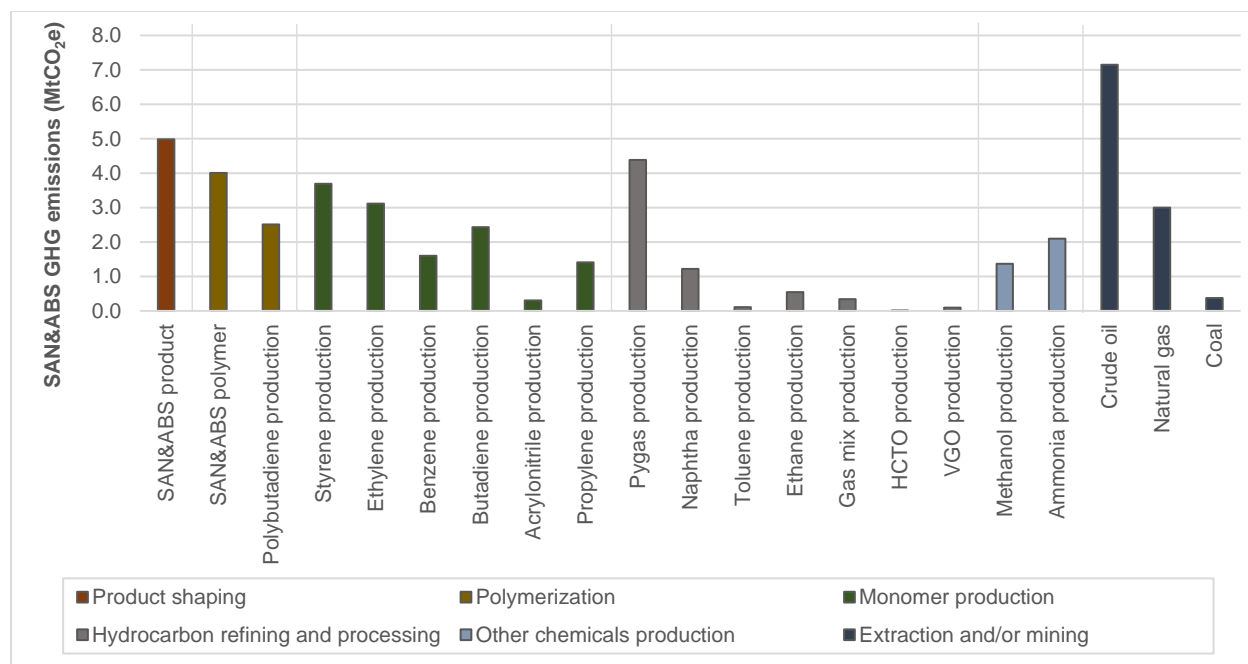
Figure 37. Breakdown of GHG emissions associated with global SAN and ABS production in 2019.

The production of PU primary plastic polymer products results in approximately 113.6 MtCO$_2$e in 2019, of which 73% comes from pre-polymerization stages (Figure 29). GHG emissions from PU production could reach to 240.7 MtCO$_2$e under the growth scenario of 2.5%/yr; and to 344.5 MtCO$_2$e under the growth scenario of 4%/yr. The other chemicals production stage has the highest share of emissions, followed by monomer production. Figure 38 provides a detailed picture of contribution of different processes to the GHG emissions from PU production. Individually, polyol production along with PO production has significant emissions footprint. Polyol is one of the basic materials used in the production of PU, and PO is used in the production of polyol. Both polyol and PO production are energy- and GHG emissions-intensive processes (see Section 2.6 for details). Like PVC production, chlorine production also contributes significantly to the emissions from PU production. Chlorine production is a very energy-intensive process, and all three production technologies used in this analysis for chlorine production have similar energy intensities (9.3-13.3 GJ/tonne chlorine) (see Section 2.4). Similar to other polymers that use pygas, the emissions footprint of pygas is higher than other hydrocarbons. Pygas is used to produce benzene (25% of global benzene production) in addition to toluene, which is then used to produce benzene through toluene-based production processes such as transalkylation and disproportionation of toluene (25% of global p-xylene production) (see Section 3.4.2 for details). Benzene is used along with nitric acid in the production of aniline, and benzene is used in the production of ethylbenzene, which is demanded for the production of PO (See Section 2.6). Pygas is produced by steam cracking of naphtha and VGO. Steam cracking is a very energy- and GHG emission-intensive production. In addition, 50% benzene is produced by catalytic reforming of naphtha. Like in other polymers using any BTX product, the heavy dependence of naphtha and other crude oil products in PU production leads to high demand for crude oil (as the feedstock for both light and heavy naphtha production) and the emissions associated with its extraction. In the production of PU, methanol is not only used for ethylene but also for MDI production, which increases methanol's impact on GHG emissions from PU

production. Similarly, natural gas is used as feedstock for not just ethylene production, but also CO production.

Appendix Table A.20 provides more details about PU production process output volumes, energy consumption, and GHG emissions.

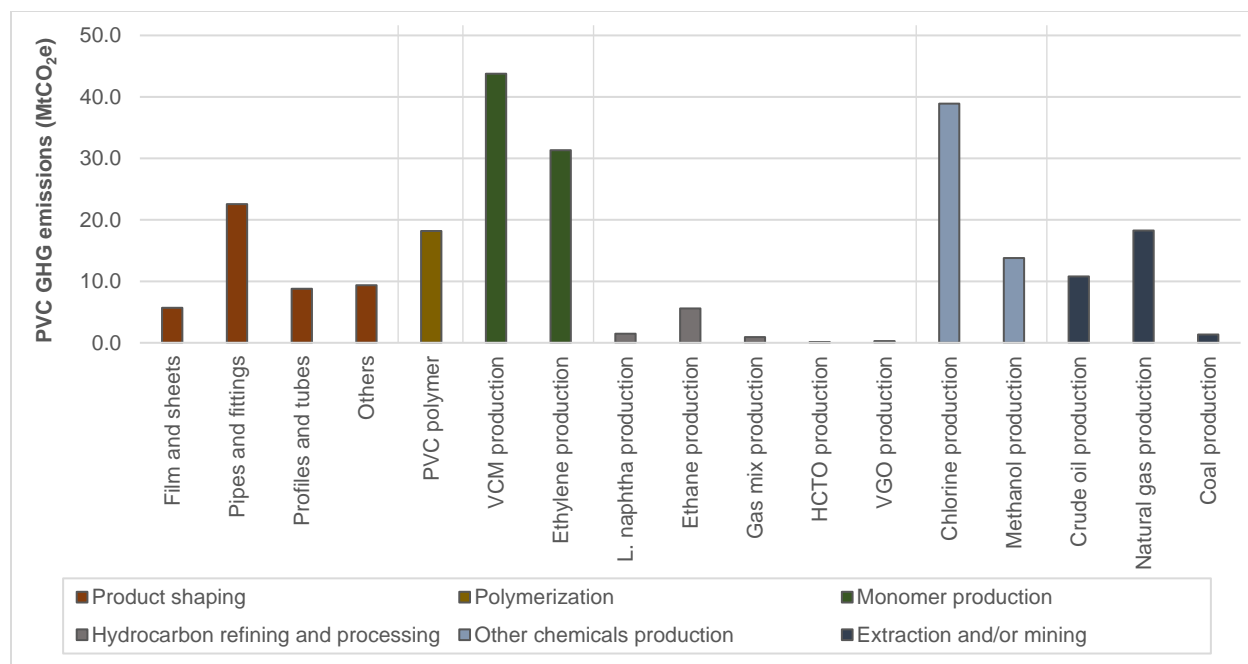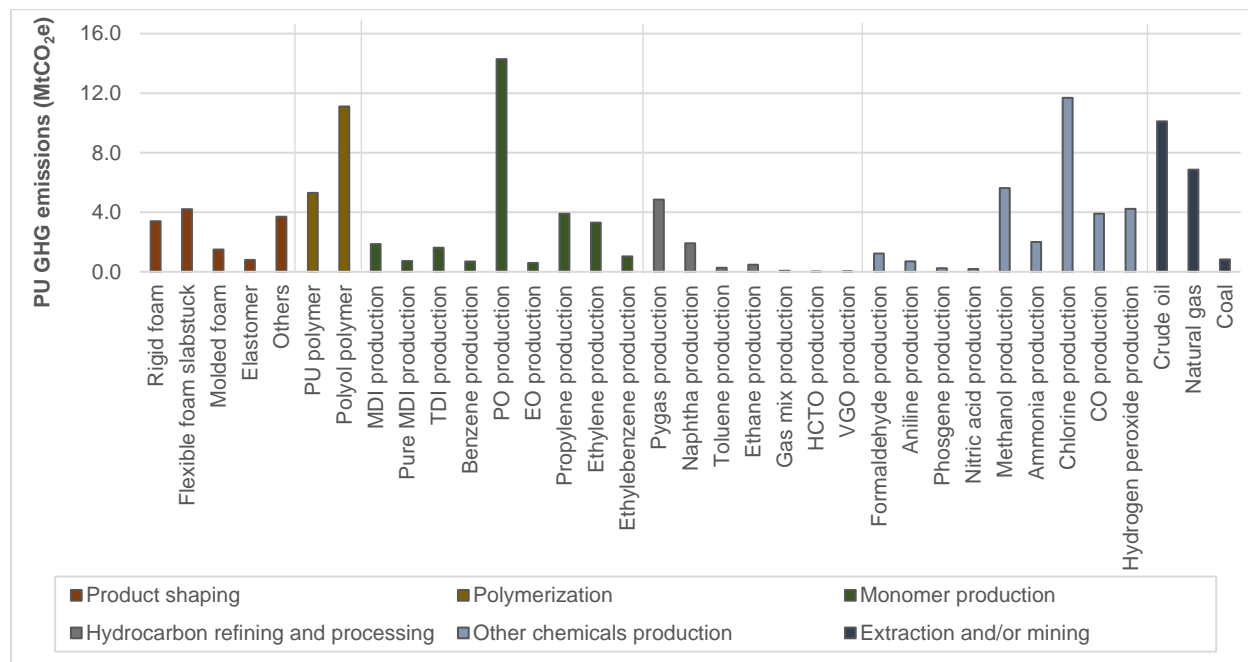*Figure 38. Breakdown of GHG emissions associated with global PU production in 2019.*

6. Conclusion

The production of most plastic products is projected to increase exponentially, stressing planetary boundaries through a triple crisis of climate change, biodiversity loss, and pollution. Plastics' impact on the climate will only grow in the coming decades, as production is expected by industry analysts to at least double by 2050. This study revealed the following main outcomes;

- The global production of plastics generated about 2.24 $GtCO_2e$ in 2019, representing 5.3% of total global GHG emissions (excluding agriculture and LULUCF). In comparison, the global aviation sector generated 0.6 $GtCO_2$ in 2019, while the global transport sector, including aviation, generated a total of 8.3 $GtCO_2$ in 2019 [243].)
- Based on the global production volumes and process-specific emission intensities, approximately 22%, 21%, and 15% of emissions related to plastic production in 2019 came from all PEs together, PET, and PP, respectively. Other key plastics, i.e., PVC, PS, SAN, ABS, and PU are responsible for around 23% of global emissions from plastic production.
- Most (~75%) emissions from plastic production occur from the steps prior to polymerization.

- Global plastic production accounted for around 12% of global oil demand and about 8.5% of global natural gas demand in 2019. Primary plastic production is heavily dependent on fossil fuels for feedstock, with as much as 70% of the fossil fuel input consumed as feedstock. This suggests that future primary plastic production could still be heavily dependent on fossil fuels for feedstock despite decarbonization of the energy system.
- Emissions from plastic production could reach 4.75 $GtCO_2e$ by 2050 under a growth scenario of 2.5%/yr, at which point they would account for 21-26% of the remaining global carbon budget to keep global average temperatures below 1.5°C. At 4% annual growth, emissions from plastic production could hit 6.78 $GtCO_2e$ by 2050, accounting for 25-31% of the remaining global carbon budget to keep average temperatures below 1.5°C. If current production levels remained constant, plastic production would still account for 15-19% of the carbon budget. These results assume that global CO_2 emission intensity of electricity generation (represented by the average global grid CO_2 emission intensity) would stay the same through the analysis period.
- Under a sensitivity analysis of decarbonized electric grid in response to stated power sector policies and targets, GHG emissions could drop to about 3.59-5.13 $GtCO_2e$ in 2050 based on 2.5-4% annual growth. Cumulative GHG emissions from plastic production could still account for 17-22% and 21-26% of the remaining carbon budget to stay below the 1.5°C threshold. Even without future growth, plastic production could still account for 13-16% of the remaining carbon budget by 2050.

The targets set out by the Paris Agreement, in which 195 countries pledged to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, reveal the urgent need for near-term and high-impact strategies to reduce emissions of all sectors. To keep global warming below 1.5°C, it is important to recognize and address the GHG emissions of plastic production in the development of policies and programs in support of global climate and plastic treaties. Currently, proposed efforts to reduce plastic pollution under the global plastics treaty overlook plastics' climate impacts. At the same time, GHG emissions from plastic production are often excluded from consideration, even in climate change-related negotiations.

This report's findings show that plastic production has a significant impact on the climate. It also highlights the importance of granularity in modelling and including all stages of production (i.e. upstream, midstream and downstream) when assessing the climate impact from plastic production. The steps prior to polymerization produced the most GHG emissions. In addition, some monomers, such as ethylene, are used almost exclusively in the production of plastics.

The magnitude of the climate impact will only increase if exponential production growth of 2.5% to 4% per year continues. Most plastic pollution mitigation strategies emphasized in the treaty process thus far (e.g., production reduction, elimination of problematic polymers, recycling, and alternative materials) could have different climate change implications, and should be rigorously investigated before a conclusion can be drawn. Eliminating non-essential use of plastics without alternatives, such as microbeads in cleaning products, could lead to a reduction in global GHG emissions from primary plastic production due to a reduction in production volume. However, the GHG impact could be different if primary plastic production is reduced by using alternative materials or recycling. For instance, mechanical recycling can lead to GHG emissions reductions

but is not applicable to all plastic polymer types. It is mostly used for PET and PE products [3], but collection, contamination, and sorting are challenges that can significantly lower the recycling efficiency [250]. In addition, the quality of the polymer often degrades with repeated recycling, so the final product may not provide the same functionality, limiting recycling to a few cycles [250]. Some chemical recycling processes use chemical processes to recover the petrochemical components in plastics, e.g., monomers and hydrocarbons, and some processes convert plastics to fuels. In order for these products to be converted back into plastic polymers, they must go through additional production stages that increase their carbon footprint. Additionally, current chemical recycling methods can require higher energy inputs than mechanical recycling [251]. Similarly, certain alternative materials to plastics can increase overall GHG emissions when produced through conventional processes. Alternative materials used also need to be recyclable in a sustainable and climate-friendly manner. Designing products with reuse, repair and remanufacturing in mind is another important consideration to reduce climate impacts. There is a need to design strategies with system-wide thinking to ensure that any set of solutions is circular, sustainable, and responsible and do not pose health risks. These demand and supply-side strategies need to consider implications from plastics pollution beyond climate to address environmental and health problems related to plastic from global and local perspectives.

In achieving the overall 1.5°C goal, it is vital to set targets for the growing plastics industry that are coordinated and scalable in the context of a broader national, regional, or international political process. Synergistic actions between global treaties are necessary to maximize the beneficial impacts of global negotiations to address the multifaceted challenges presented by plastics and climate change. The global plastic treaty presents a historic opportunity to tackle plastic pollution and also provide a level playing field to design upstream, midstream, and downstream policies and measures to address GHG emissions from the primary plastic production globally and at scale.

For future work, we plan to expand our modeling framework to include recycling methods and the production of alternative materials to plastic in order to evaluate the climate impact of various mitigation strategies that may include these actions. We also plan to extend the modelling from global scale to incorporate regional details as the improved geographic granularity could help better inform the setting of region or national goals and actions.

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Climate Impact of Primary Plastic Production

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SUPPLEMENTARY APPENDICES

Appendix A

Data and assumptions

LDPE & LLDPE
- 1%
- 5%
- 13%
- 3%
- 8%
- 70%

Legend: Construction, Consumer products, Electrical/electronic, Other, Packaging, Vehicles

HDPE
- 5%
- 19%
- 11%
- 1%
- 8%
- 56%

Legend: Construction, Consumer products, Electrical/electronic, Other, Packaging, Vehicles

PP
- 8%
- 6%
- 16%
- 22%
- 5%
- 1%
- 43%

Legend: Construction, Consumer products, Electrical/electronic, Other, Packaging, Vehicles, Fibers

PET
- 34%
- 66%

Legend: Packaging, Fibers

Figure A.1. Distribution of global finished plastic products in 2019, by polymer and application type.

Notes: LDPE = Low-density polyethylene, LLDPE = Linear low-density polyethylene, HDPE = High-density polyethylene, PP = Polypropylene, PET = Polyethylene terephthalate, PVC = Polyvinyl chloride, PS = Polystyrene, SAN = Styrene Acrylonitrile, ABS = Acrylonitrile Butadiene Styrene, PU = Polyurethane. PET in chart includes polyester fibers in addition to films and other PET products used for packaging such as PET bottles.
Source: [3]

Table A.1. Energy intensity of different product shaping processes assumed for plastic products in this analysis.

Product	Process type	Energy intensity (GJ/tonne)
LDPE	Injection molding	9.2
	Blow molding	7.0
	Film extrusion	5.3

	Other extrusion	13.7
	Others	12.1
LLDPE	Injection molding	9.2
	Rotational molding	21.2
	Film extrusion	4.7
	Others	12.9
HDPE	Injection molding	10.1
	Blow molding	8.0
	Film extrusion	4.1
	Other extrusion	13.7
	Others	12.1
PP	Injection molding	9.2
	Blow molding	7.0
	Extrusion	5.5
	Fiber	6.3
	Others	8.3
PET	Film	5.3
	Solid state (injection, blow molding, and extruding)	7.8
	Fiber	6.2
PVC	Films and sheets	5.6
	Pipes and fittings	8.6
	Profiles and tubes	9.5
	Others	7.5
PS	GPPS	8.2
	HIPS	6.5
	EPS and XPS	6.8
	XPS	6.8
PS	ABS	4.8
SAN and ABS	Others	6.6
PUR	Rigid foam	6.5
	Flexible foam	4.8
	Flexible foam slabstuck	4.8
	Molded foam	7.2
	Elastomer	7.8
	Others	6.2

Notes: LDPE = low-density polyethylene, LLDPE = linear low-density polyethylene, HDPE = high-density polyethylene, PP = polypropylene, PET = polyethylene terephthalate, PVC = polyvinyl chloride, PS = polystyrene, GPPS = general purpose polystyrene, HIPS = high impact polystyrene, EPS = expanded polystyrene, XPS = extruded polystyrene, SAN = styrene acrylonitrile, ABS = acrylonitrile butadiene styrene, PU = polyurethane.

Source: [45,131,142-146,148,149,252,253]

Table A.2. Shares of fuels used in manufacturing of finished plastic products by manufacturing type, assumed in this analysis

Process type	Electricity	Heating Oil	Natural gas
Injection molding	81%	7%	13%
Blow molding	92%	3%	5%
Film extrusion	79%	15%	6%
Other extrusion	80%	11%	10%
Others	79%	6%	15%

Notes: Shares only represent fuels used for process energy for heat and electricity. "Other extrusion" include profile and sheet extrusion, monofilament extrusion, etc. "Others" include compression molding, thermoforming, fiber extrusion, and etc.
Source: [75,148]

Table A.3. Energy intensity of polymerization processes assumed for plastic polymers in this analysis.

Plastic product	Energy intensity (GJ/tonne)
LDPE	5.2
LLDPE	3.6
HDPE	3.25
PP	3.7
PET	3.5
PET with solid state	3.9
PVC-suspension	3.4
PVC-emulsion	8.4
PVC-bulk	Assumed same as suspension PVC
GPPS	2.5
HIPS	2.7
EPS	2.9
XPS	Assumed same as HIPS
Other PS	Assumed same as HIPS
SAN	Assumed same as ABS
ABS	3.5
PUR	1.5
Polybutadiene	5.1

Notes: LDPE = low-density polyethylene, LLDPE = linear low-density polyethylene, HDPE = high-density polyethylene, PP = polypropylene, PET = polyethylene terephthalate, PVC = polyvinyl chloride, PS = polystyrene, GPPS = general purpose polystyrene, HIPS = high impact polystyrene, EPS = expanded polystyrene, XPS = extruded polystyrene, SAN = styrene acrylonitrile, ABS = acrylonitrile butadiene styrene, PU = polyurethane.
Source: [49-55]

Table A.4. Type of fuels used in polymerization by polymer type, assumed in this analysis (UPDATE)

Plastic product	Electricity	Heating Oil	Natural gas
PE	100%		
PP	100%		

PET	10%	45%	45%
PVC-suspension	29%	71%	
PVC-emulsion	19%	81%	
PVC	36%	64%	
GPPS	59%	41%	0%
HIPS	36%	64%	0%
ABS	57%	16%	27%
Other PS	25%	51%	25%
PUR	100%		
Polybutadiene	13%	43%	43%

Notes: LDPE = low-density polyethylene, LLDPE = linear low-density polyethylene, HDPE = high-density polyethylene, PP = polypropylene, PET = polyethylene terephthalate, PVC = polyvinyl chloride, PS = polystyrene, GPPS = general purpose polystyrene, HIPS = high impact polystyrene, EPS = expanded polystyrene, XPS = extruded polystyrene, SAN = styrene acrylonitrile, ABS = acrylonitrile butadiene styrene, PU = polyurethane. Source: [31,46,52,110]

Table A.5. Type of fuels used in VCM and chlorine production, assumed in this analysis

	Electricity	Heating oil	Natural gas
VCM	33%	1%	66%
Chlorine	100%		

Notes: VCM = vinyl chloride monomer.
Source: [49,98]

Table A.6. Process yields, energy consumption, and fugitive emissions from other light hydrocarbons and distillate fuel oils-based steam cracking

"Gas mix" based steam cracking		
	Literature range	This study
Ethylene (Yield (%))	37-46.5%	42.5%
Propylene (Yield (%))	12.5-19%	17.0%
Butadiene (Yield (%))	1.8-4.8%	3.3%
Benzene (Yield (%))	2.4-3%	2.7%
Energy consumption (GJ/tonne HVC)	16-19.2 GJ/tonne HVC	17.6 GJ/tonne HVC
Fugitive CH4 emissions (tCO$_2$eq./t HVC)	0.09tCO$_2$eq./t HVC	0.09 tCO$_2$eq./t HVC
VGO-based steam cracking		
	Literature range	This study
Ethylene (Yield (%))	25-28%	26.5%
Propylene (Yield (%))	14%	14.0%
Butadiene (Yield (%))	5-5.8%	5.4%
Benzene (Yield (%))	5-5.5%	5.3%
P-xylene (Yield (%))	0.8%	0.8%
Energy consumption (GJ/tonne HVC)	12-20.1 GJ/tonne HVC	16.1 GJ/tonne HVC from VGO
Energy consumption (GJ/tonne HVC)	12-20.1 GJ/tonne HVC	18.2 GJ/tonne HVC from HCTO
Fugitive CH4 emissions (tCO$_2$eq./t HVC)	0.09 tCO$_2$eq./t HVC	0.09 tCO$_2$eq./t HVC

Table A.7. Shares of fuels used in steam cracking process, assumed in this analysis

	Electricity	Residual oil/VGO/Heating	Natural gas	Coal
Steam cracking of light	2%	98%	0%	
Steam cracking of ethane	3%	0%	97%	
Steam cracking of Gas mix	3%	58%	39%	
Steam cracking of VGO and HCTO	2%	98%	0%	
MTO	23%	0%	77%	
CMTO	23%	0%	0%	77%

Notes: VGO = Vacuum gas oil, HCTO = hydro cracking tail oil, MTO = methanol to olefin, CMTO = coal-based methanol to olefin.
Source: [40,48,157,180]

Table A.8. Type of fuels used in petroleum refineries and natural gas processing plants assumed in this analysis

	Electricity	Residual oil/VGO/heating oil	Natural gas	Refinery gas	Petroleum coke	Offsite steam
Petroleum refinery	4.5%	1.4%	26.0%	51.6%	12.7%	3.8%
Natural gas processing plant	61.4%	3.4%	35.2%			

Source: [41,167,178,193,194]

Table A.9. Distribution of GHG emissions from global petroleum refineries and natural gas processing plants assumed in the analysis

	Fuel combustion (%)	Process emission (%)		
	CO_2	CO_2	CH_4	N_2O
Refinery emissions for production of Light and Heavy Naphtha, Gas mix, VGO, HCTO	87.0%	12.2%	0.5%	0.3%
Refinery emissions for FCC process	71.3%	27.9%	0.5%	0.3%
Natural gas processing emissions for production of ethane and gas mix	91.0%		9.0%	

Notes: VGO = Vacuum gas oil, HCTO = hydro cracking tail oil, FCC = fluid catalytic cracking.
Source: [41,148,200,202,207]

Table A.10. Methanol production conversion efficiency by feedstock assumed in this analysis

	Natural gas	Coal	Coke gas
Process conversion efficiency	71%	55%	55%

Source: [179,221]

Table A.11. Emission factors by fuel type assumed in this analysis

	Emission factor (kgCO$_2$/GJ)
Coal	94.6
Gas	56.1
Oil (gas, diesel, other)	73.3
Refinery gas	57.6
Petroleum coke	97.5
Coke oven gas	52.6
Residual fuel oil	77
Gasoline	69
Electricity	128
Offsite steam	56.1

Notes: Emission factor for "Electricity" presents the CO$_2$ emission intensity of the power grid in 2022.
Source: [242,254]
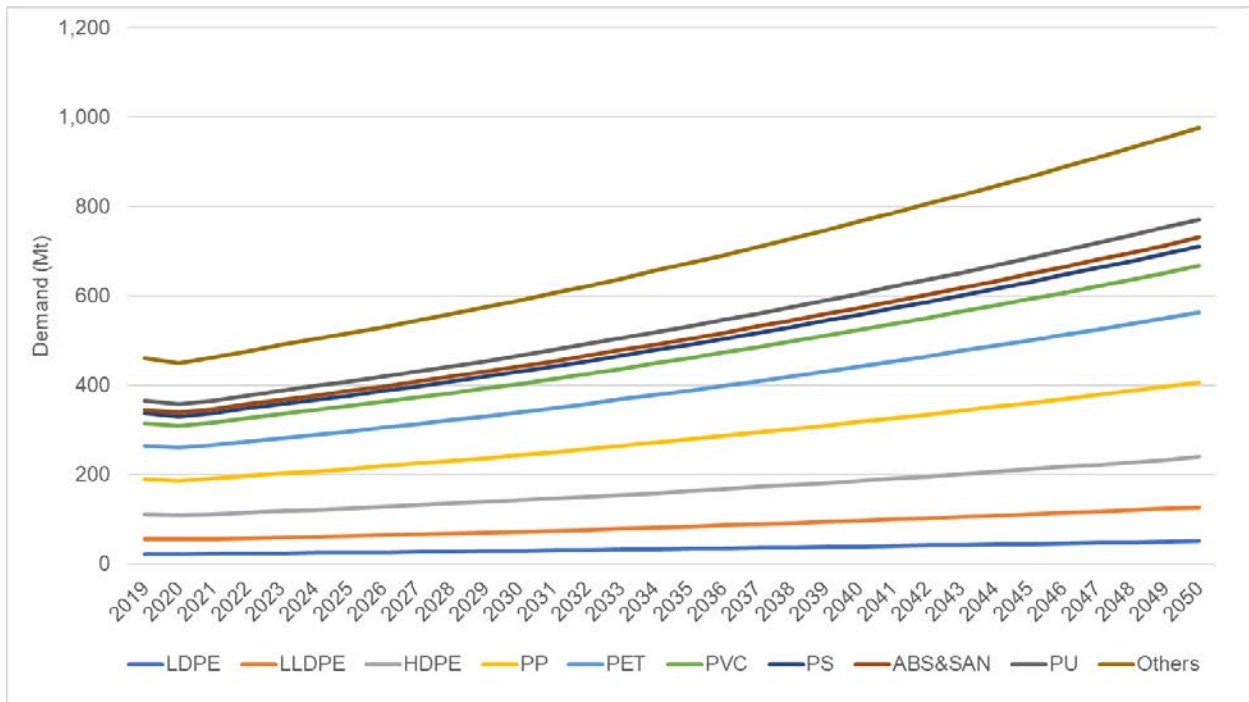
Figure A.2. Plastic demand between 2019 and 2050 per polymer type, assumed in the 2.5% annual growth scenario.

Source: [3]
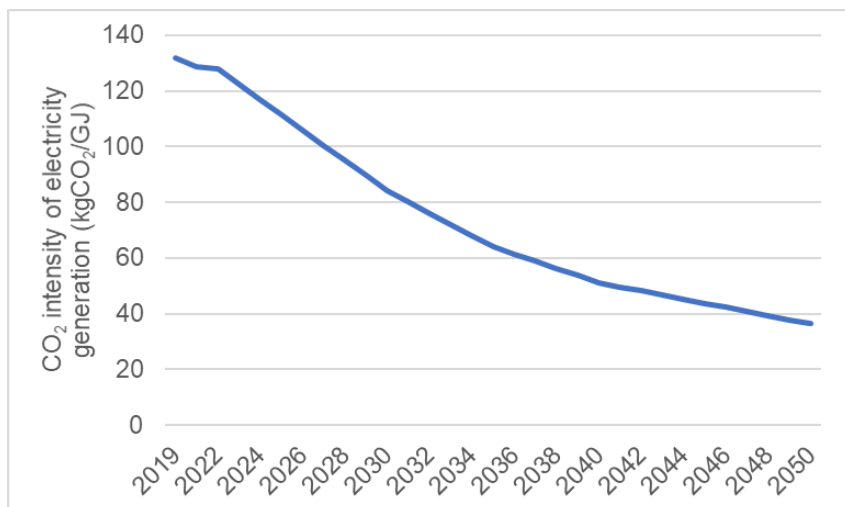
Figure A.3. CO₂ intensity of electricity generation between 2019 and 2050 under decarbonized grid assumed in this analysis.

Source: CO₂ emissions intensity trend in this chart are based on IEA's projections for Stated Policies Scenario (STEPS) [242].

Appendix B

Detailed plastic results

Table A.12. Details of global LDPE production and associated energy demand and GHG emissions in 2019

	Demand (Mt)	Energy consumption (PJ)	GHG Emissions (MtCO₂e)
Product shaping	**20.9**	**149.9**	**17.8**
->Injection molding	1.4	12.9	1.5
->Blow molding	0.4	2.7	0.3
->Film extrusion	14.6	77.2	9.2
->Other extrusion	2.0	27.1	3.2
->Others	2.5	30.1	3.5
Polymerization	**21.1**	**110.0**	**12.7**
->LDPE polymer	21.1	110.0	12.7
Monomer production	**21.5**	**368.2**	**28.2**
->Ethylene production	21.5	368.2	28.2
->from SC of Light Naphtha	7.7	142.5	11.8
->from SC of Ethane	8.4	142.8	9.8
->from SC of Gas mix	3.4	60.6	4.6
->from SC of HCTO	0.1	2.1	0.2
->from SC of VGO	1.1	17.9	1.5
->from MTO of methanol	0.8	2.3	0.3
Hydrocarbon refining and processing	**22.4**	**76.5**	**7.5**

->Light naphtha production	7.3	17.2	1.3
->Ethane production	10.2	43.5	4.9
->Gas mix production	3.5	10.9	1.0
->HCTO production	0.4	1.6	0.1
->VGO production	1.1	3.3	0.2
Other chemicals production	**3.8**	**134.2**	**12.1**
->Methanol production	3.8	134.2	12.1
Extraction and/or mining	**39.8**		**20.2**
->Crude oil production	16.1		7.4
->Feedstock	10.8		5.0
->Energy	5.2		2.4
->Natural gas production	17.6	N.A	11.7
->Feedstock	12.9		8.5
->Energy	4.7		3.1
->Coal production	6.2		1.2
->Feedstock	3.37		0.64
->Energy	2.8		0.5

Table A.13. Details of global LLDPE production and associated energy demand and GHG emissions in 2019

	Demand (Mt)	Energy consumption (PJ)	GHG Emissions (MtCO$_2$e)
Product shaping	**31.3**	**238.4**	**28.9**
->Injection molding	3.9	36.0	4.3
->Rotational molding	3.9	83.1	10.5
->Film extrusion	22.4	105.8	12.6
->Others	1.0	13.4	1.6
Polymerization	**31.6**	**114.8**	**13.3**
->LLDPE polymer	31.6	114.8	13.3
Monomer production	**36.2**	**576.5**	**44.5**
->Ethylene production	33.3	570.6	43.7
->from SC of Light Naphtha	12.0	220.9	18.3
->from SC of Ethane	13.0	221.3	15.2
->from SC of Gas mix	5.3	93.8	7.1
->from SC of HCTO	0.2	3.2	0.3
->from SC of VGO	1.7	27.8	2.3
->from MTO of methanol	1.2	3.6	0.4
->LAO production	2.8	5.9	0.8
Hydrocarbon refining and processing	**34.7**	**118.5**	**11.7**
->Light naphtha production	11.3	26.7	2.0
->Ethane production	15.8	67.4	7.6
->Gas mix production	5.4	16.9	1.5
->HCTO production	0.6	2.5	0.2
->VGO production	1.7	5.1	0.4
Other chemicals production	**5.9**	**208.0**	**18.7**

->Methanol production	5.9	208.0	18.7
Extraction and/or mining	**61.5**		**31.2**
->Crude oil production	24.8		11.4
->Feedstock	16.8		7.7
->Energy	8.0		3.7
->Natural gas production	27.1	N.A	18.0
->Feedstock	19.9		13.2
->Energy	7.2		4.8
->Coal production	9.6		1.8
->Feedstock	5.2		0.99
->Energy	4.3		0.8

Table A.14. Details of global HDPE production and associated energy demand and GHG emissions in 2019

	Demand (Mt)	Energy consumption (PJ)	GHG Emissions (MtCO$_2$e)
Product shaping	**51.2**	**447.1**	**53.7**
->Injection molding	9.3	93.8	11.1
->Blow molding	12.5	99.9	12.6
->Film extrusion	14.3	58.7	7.0
->Other extrusion	7.7	105.1	12.4
->Others	7.4	89.6	10.5
Polymerization	**51.7**	**168.0**	**19.5**
->HDPE polymer	51.7	168.0	19.5
Monomer production	**54.2**	**915.7**	**68.3**
->Ethylene production	53.4	914.1	68.1
->from SC of Naphtha	19.2	353.8	28.1
->from SC of Ethane	20.8	354.5	24.4
->from SC of Gas mix	8.5	150.3	11.0
->from SC of HCTO	0.3	5.2	0.4
->from SC of VGO	2.7	44.5	3.6
->from MTO of methanol	1.9	5.8	0.5
->LAO production	0.8	1.6	0.2
Hydrocarbon refining and processing	**55.7**	**189.9**	**18.8**
->Light naphtha	18.1	42.7	3.2
->Ethane	25.3	107.9	12.2
->Gas mix	8.7	27.1	2.4
->HCTO	0.9	4.1	0.3
->VGO	2.7	8.1	0.6
Other chemicals production	**9.5**	**333.2**	**29.9**
->Methanol	9.5	333.2	29.9
Extraction and/or mining	**98.8**	N.A	**50.2**
->Crude oil	39.7		18.2

->Feedstock	26.9		12.3
->Energy	12.7		5.8
->Natural gas	43.9		29.1
->Feedstock	31.9		21.2
->Energy	11.9		7.9
->Coal	15.3		2.9
->Feedstock	8.37		1.59
->Energy	6.9		1.3

Table A.15. Details of global PP production and associated energy demand and GHG emissions in 2019

	Demand (Mt)	Energy consumption (PJ)	GHG Emissions (MtCO$_2$e)
Product shaping	**74.8**	**583.3**	**69.5**
->Injection molding	28.5	263.0	31.2
->Blow molding	10.3	72.0	9.1
->Extrusion	8.0	44.1	5.2
->Fiber	14.1	89.6	10.6
->Others	13.9	114.6	13.4
Polymerization	**75.6**	**282.0**	**37.2**
->PP polymer	75.6	282.0	37.2
Monomer production	**88.5**	**1,162.1**	**95.4**
->Propylene production	85.2	1105.8	91.2
->from SC	41.3	675.3	53.1
->from FCC	29.3	272.6	20.3
->from PDH	8.5	114.3	11.9
->from MTO/MTP of methanol	3.9	28.6	3.9
->from Others (e.g.,Metathesis and Superflex)	2.3	15.0	2.0
->Other Olefins production	3.3	56.3	4.2
Hydrocarbon refining and processing	**75.1**	**217.6**	**22.5**
->Light naphtha	20.9	49.2	3.9
->Ethane	1.6	6.7	0.8
->Gas mix	20.2	63.0	10.3
->HCTO	0.1	0.3	0.0
->VGO	32.4	98.5	7.5
Other chemicals production	**18.0**	**628.5**	**56.0**
->Methanol	18.0	628.5	56.0
Extraction and/or mining	**125.3**		**54.2**
->Crude oil	73.6		33.7
->Feedstock	65.4	N.A	30.0
->Energy	8.1		3.7
->Natural gas	22.6		15.0

->Feedstock	15.6		10.4
->Energy	6.9		4.6
->Coal	29.1		5.5
->Feedstock	15.80		3.00
->Energy	13.3		2.5

Table A.16. Details of global PET production and associated energy demand and GHG emissions in 2019

	Demand (Mt)	Energy consumption (PJ)	GHG Emissions (MtCO2e)
Product shaping	**71.7**	**477.6**	**56.0**
->Film	1.6	8.3	1.0
->Solid state	21.4	166.7	19.5
->Fiber	48.8	302.5	35.5
Polymerization	**72.4**	**261.7**	**18.7**
->PET polymer	72.4	261.7	18.7
Monomer production	**102.9**	**883.4**	**66.9**
->PTA production	61.6	456.7	30.6
->EG production	25.4	153.2	10.8
->Ethylene production	16.0	273.5	25.6
Hydrocarbon refining and processing	**289.9**	**2,348.5**	**180.9**
->Pygas	64.4	105.9	92.2
->P-xylene	48.2	807.0	52.9
->Toluene	34.6	105.9	6.7
->Naphtha (light+heavy)	121.0	181.0	22.4
->Ethane	7.6	32.3	3.5
->Gas mix	2.6	8.1	0.7
->HCTO	0.3	1.2	0.1
->VGO	11.3	34.4	2.4
Other chemicals production	**12.8**	**338.0**	**30.5**
->Acetic acid	3.3	7.1	0.8
->Methanol	9.5	330.9	29.7
Extraction	**237.6**		**111.6**
->**Crude oil**	189.9		87.0
->Feedstock	134.2		61.5
->Energy	55.7		25.5
->**Natural gas**	32.6	N.A	21.6
->Feedstock	12.2		8.1
->Energy	20.4		13.5
->**Coal**	15.1		2.9
->Feedstock	8.32		1.62
->Energy	6.8		1.3

Table A.17. Details of global PVC production and associated energy demand and GHG emissions in 2019

	Demand (Mt)	Energy consumption (PJ)	GHG Emissions (MtCO$_2$e)
Product shaping	**48.5**	**387.9**	**46.5**
->Film and sheets	8.5	47.6	5.7
->Pipes and fittings	21.8	188.2	22.6
->Profiles and tubes	7.8	74.0	8.8
->Others	10.4	78.1	9.4
Polymerization	**49.0**	**189.5**	**18.2**
->PVC polymer	49.0	189.5	18.2
Monomer production	**78.0**	**954.3**	**75.1**
->VCM production	53.4	533.6	43.8
->Ethylene production	24.6	420.7	31.3
->from SC of Light Naphtha	8.8	162.9	12.9
->from SC of Ethane	9.6	163.1	11.2
->from SC of Gas	3.9	69.2	5.1
->from SC of HCTO	0.1	2.4	0.2
->from SC of VGO	1.2	20.5	1.6
->from MTO of methanol	0.9	2.7	0.2
Hydrocarbon refining and processing	**25.6**	**87.4**	**8.4**
->Light naphtha production	8.3	19.7	1.5
->Ethane production	11.6	49.7	5.6
->Gas mix production	4.0	12.5	0.9
->HCTO production	0.4	1.9	0.1
->VGO production	1.2	3.7	0.3
Other chemicals production	**84.5**	**448.2**	**52.7**
->Chlorine	26.7	294.9	38.9
->Methanol	4.4	153.3	13.8
Extraction and/or mining	**53.2**		**30.4**
->Crude oil	23.6		10.8
->Feedstock	12.4		5.7
->Energy	11.2		5.1
->Natural gas	22.6	N.A	18.3
->Feedstock	9.7		9.7
->Energy	12.9		8.5
->Coal	7.0		1.3
->Feedstock	3.85		0.73
->Energy	3.2		0.6

Table A.18. Details of global PS production and associated energy demand and GHG emissions in 2019

	Demand (Mt)	Energy consumption (PJ)	GHG Emissions (MtCO2e)
Product shaping	**20.6**	**141.3**	**17.0**
->GPPS	2.7	21.8	2.6
->HIPS	7.2	46.9	5.6
->EPS	7.4	50.4	6.1
->XPS	2.1	14.0	1.7
->Others	1.2	8.1	1.0
Polymerization	**20.9**	**60.4**	**7.2**
->PS polymer	20.8	57.2	7.0
->Polybutadiene polymer	0.2	3.2	0.2
Monomer production	**60.1**	**545.3**	**41.0**
->Styrene production	23.8	228.1	18.0
->Ethylene production	11.9	203.6	15.2
->Benzene production	24.3	110.4	7.6
->Butadiene production	0.2	3.2	0.2
Hydrocarbon refining and processing	**56.9**	**362.6**	**28.9**
->Pygas	14.9	273.3	21.4
->Naphtha (light+heavy)	31.1	48.7	3.6
->Toluene	2.6	7.8	0.5
->Ethane	5.6	24.0	2.7
->Gas mix	1.9	6.0	0.4
->HCTO	0.2	0.9	0.1
->VGO	0.6	1.8	0.1
Other chemicals production	**2.1**	**74.2**	**6.7**
->Methanol	2.1	74.2	6.7
Extraction	**64.0**		**31.0**
->Crude oil	49.9		22.9
->Feedstock	33.0		15.1
->Energy	16.8		7.7
->Natural gas	11.4	N.A	7.5
->Feedstock	7.2		4.7
->Energy	4.2		2.8
->Coal	2.7		0.7
->Feedstock	1.17		0.38
->Energy	1.5		0.3

Table A.19. Details of global SAN and ABS production and associated energy demand and GHG emissions in 2019

	Demand (Mt)	Energy consumption (PJ)	GHG Emissions (MtCO2e)

Product shaping	**8.9**	**42.5**	**5.0**
->SAN,ABS	8.9	42.5	5.0
Polymerization	**10.8**	**65.8**	**6.5**
->ABS&SAN polymer	9.0	31.7	4.0
->Polybutadiene polymer	1.8	34.1	2.5
Monomer production	**18.4**	**165.8**	**12.3**
->Styrene	4.9	46.8	3.7
->Ethylene	2.4	41.8	3.1
->Benzene	5.0	22.7	1.6
->Butadiene	1.8	33.3	2.4
->Acrylonitrile	2.1	2.3	0.3
->Propylene	2.2	18.9	1.4
Hydrocarbon production	**46.8**	**85.1**	**6.7**
->Pygas	3.1	56.1	4.4
->Naphtha (light+heavy)	40.0	15.9	1.2
->Toluene	0.5	1.6	0.1
->Ethane	1.2	4.9	0.5
->Gas mix	1.6	5.0	0.3
->HCTO	0.0	0.2	0.0
->VGO	0.5	1.5	0.1
Other chemicals production	**2.0**	**43.4**	**3.5**
->Methanol	0.4	15.2	1.4
->Ammonia	1.6	28.2	2.1
Extraction	**22.1**		**10.5**
->Crude oil	15.6		7.1
->Feedstock	10.4		4.7
->Energy	5.2		2.4
->Natural gas	4.5	N/A	3.0
->Feedstock	2.7		1.8
->Energy	1.8		1.2
->Coal	2.0		0.4
->Feedstock	1.09		0.21
->Energy	0.9		0.2

Table A.20. Details of global PU production and associated energy demand and GHG emissions in 2019

	Demand (Mt)	Energy consumption (PJ)	GHG Emissions (MtCO$_2$e)
Product shaping	**19.18**	**115.7**	**13.6**
->Rigid foam	4.80	31.4	3.4
->Flexible foam slabstuck	5.95	28.2	4.2
->Molded foam	2.11	15.2	1.5

->Elastomer	1.15	8.8	0.8
->Others	5.18	32	3.7
Polymerization	**28.9**	**200.2**	**16.4**
->PU polymer	19.4	29.7	5.3
->Polyol polymer	9.6	170.5	11.1
Monomer production	**36.4**	**381.2**	**28.0**
->MDI	6.0	25.1	1.9
->Pure MDI	2.3	9.6	0.7
->TDI	2.4	27.0	1.6
->Benzene	6.2	10.0	0.7
->PO	7.9	203.6	14.3
->EO	1.0	10.2	0.6
->Propylene	6.0	52.4	3.9
->Ethylene	2.0	34.6	3.3
->Ethylebenzene	2.5	8.6	1.0
Hydrocarbon refining and processing	**20.7**	**97.3**	**7.6**
->Pygas	3.8	62.0	4.8
->Naphtha (light+heavy)	14.0	25.5	1.9
->Toluene	1.4	4.3	0.3
->Ethane	1.0	4.1	0.5
->Gas mix	0.3	1.0	0.1
->HCTO	0.0	0.2	0.0
->VGO	0.1	0.3	0.0
Other chemicals production	**25.2**	**298.6**	**29.8**
->Formaldehyde	2	15.0	1.2
->Aniline	4.4	8.2	0.7
->Phosgene	7.1	3.4	0.2
->Nitric acid	1.3	2.1	0.2
->Methanol	2.1	62.5	5.6
->Ammonia	1.5	27.0	2.0
->Chlorine	8	88.6	11.7
->CO	1.9	59.7	3.9
->Hydrogen peroxide	0.6	32.0	4.2
Extraction and/or mining	**36.8**		**17.8**
->Crude oil	22.0		10.1
->Feedstock	14.4		6.6
->Energy	7.7	N.A	3.5
->Natural gas	10.3		6.9
->Feedstock	2.6		1.7
->Energy	7.8		5.2
->Coal	4.4		0.8

->Feedstock	2.6		0.5
->Energy	1.8		0.3

Energy consumption of primary plastic production estimated in this study

This section compares our estimates of energy consumption for primary plastic production with selected studies in the literature. Our energy demand results for some primary plastics (including feedstock and process energy) are close to some analyzes in the literature, while others are significantly different (Table 17). However, most of these analyzes are not direct points of comparison. For example, although analysis boundary of Nicholson et al. [46] is similar to ours, their energy results include different items, for example, energy for electricity generation and transportation. Our energy consumption estimates represent final energy and do not include transportation of intermediate products between facilities. Plastics Europe [98] and Marczak [149] provides energy consumption for resin, which is the energy combusted up until polymer production and does not include product shaping. Product shaping processes would bring about an additional 4-21 GJ/tonne product, depending on the process and polymer type.

As can be seen from Table 17, none of the analyses listed has a global scope, but they represent production in a particular region (namely, US and Europe). As mentioned earlier in the report, a production route that is indicative of a primary plastic polymer production in a particular region may not be representative of other regions. For example, ethane-based steam cracking in the U.S. versus naphtha-based steam cracking in Europe will have very different emission factors despite producing the same monomers and polymers. Nicholson et al. [46] and Keoleian et al. [255] focused exclusively on US manufacturing, which is mostly based on steam cracking of ethane for ethylene production. Similarly, Plastics Europe [98] and Marczak [149] represented Europe, which mainly uses steam cracking of naphtha for ethylene production, in their analysis. In addition, none of these analyses consider MTO as a production process for ethylene (so for PEs), which has significantly higher total production chain energy consumption and emissions compared to steam cracking-based production processes. Similarly, none of these analyses include PDH, MTO, MTP, and other propylene production routes for PP production in their energy consumption estimates.

Additionally, there is not enough transparency regarding production processes and materials in the existing literature. Some products may be considered as by-products of other materials' production streams. For example, we notice that pygas (a hydrocarbon used for heavily for PET, and PS production) is often called a by-product of steam cracking process for ethylene production in most of the literature. If we remove the energy consumption associated with pygas from our analysis, the energy intensity levels of PET and PS drop to levels much closer to those presented in Table 17. Similarly, some of these literature does not discuss any toluene-based p-xylene production in their background information.

This is in line with recent discussions about the need to re-examine the carbon footprint of products made from fossil fuels, including plastics [256]. Discussions are based on the latest

updates from Ecoinvent and Plastic Europe.[22] The latest version of Ecoinvent improves data presentation and transparency for essential chemical precursors and their derivatives, such as ethylene, propylene, butadiene, benzene, toluene, and xylenes, ethylene oxide, and ethylene glycol, in terms of technological and geographical coverage. Plastics Europe [98] statistics in Table 17 are based on chemical representations in previous versions and do not include the latest updates.

Table A.21. Comparison of energy demand of our analysis with literature

	Energy demand (for both feedstock and fuel)
	GJ/tonne LDPE
Our analysis - Global	97.4 (for product)
Nicholson et al. [46] - US	82-97 (for product)*
Keoleian et al. [255] - US	94.8 (product)
Marczak [149] - EU	64.6-92 (resin)
Plastics Europe [98] - EU	81.5 (resin)
	GJ/tonne LLDPE
Our analysis – Global	99.1 (product)
Nicholson et al. [46] - US	79-91 (product)
Keoleian et al. [255] - US	86.1 (product)
Plastics Europe [98] - EU	78.3 (resin)
	GJ/tonne HDPE
Our analysis - Global	98 (product)
Nicholson et al. [46] - US	73-80 (product)
Keoleian et al. [255] - US	89.5 (product)
Plastics Europe [98] - EU	79.3 (resin)
	GJ/tonne PP
Our analysis - Global	92.2 (product)
Nicholson et al. [46] - US	92-96 (product)
Keoleian et al. [255] - US	89.1 (product)
Marczak [149] - EU	64-111.5 (resin)
Plastics Europe [98] - EU	77.9 (resin)
Russo et al. [44] – EU	85.2 (resin)
	GJ/tonne PET
Our analysis - Global	154.2 (product)
Nicholson et al. [46] - US	107-125 (product)
Keoleian et al. [255] - US	78.5 (product)
Marczak [149] - EU	109.2-115.2 (resin)
Plastics Europe [98] - EU	71.2 (resin)
	GJ/tonne PVC

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[22] Ecoinvent is a sectoral database. Ecoinvent Version 3.10 is the newest version (March 12, 2024). Industry database for plastics production for European conditions was provided by Plastics Europe to Ecoinvent [257].

Our analysis - Global	65.7 (product)
Nicholson et al. [46] - US	70-72 (product)
Keoleian et al. [255] - US	63.4 (product)
Marczak [149] - EU	52.4-79.5 (resin)
Plastics Europe [98] - EU	57.8-61.1 (resin)
	GJ/tonne PS
Our analysis - Global	147.7 (product)
Nicholson et al. [46] - US	74-86 (product)
Keoleian et al. [255] - US	88.6-89.4 (resin)
Marczak [149] - EU	70.8–118 (resin)
Plastics Europe [98] - EU	82.8-84.2(resin)
	GJ/tonne ABS
Our analysis - Global	114.3 (product)
Nicholson et al. [46] - US	90 (product)
Keoleian et al. [255] - US	112.4 (product)
Plastics Europe [98] - EU	92.6 (resin)
	GJ/tonne PU
Our analysis – Global	99.7 (product)
Nicholson et al. [46] – US	64-153 (product)
Keoleian et al. [255] - US	74.7-79.9 (resin)
Russo et al. [43] – EU	82.4 (resin)
Plastics Europe [98] – EU	82.5-105.5 (resin)