Climate Impact of Primary Plastic Production

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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.[1]

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

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

fuels to shaping of the final product), processes and technologies used in polymer production value chains. [2] 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 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].

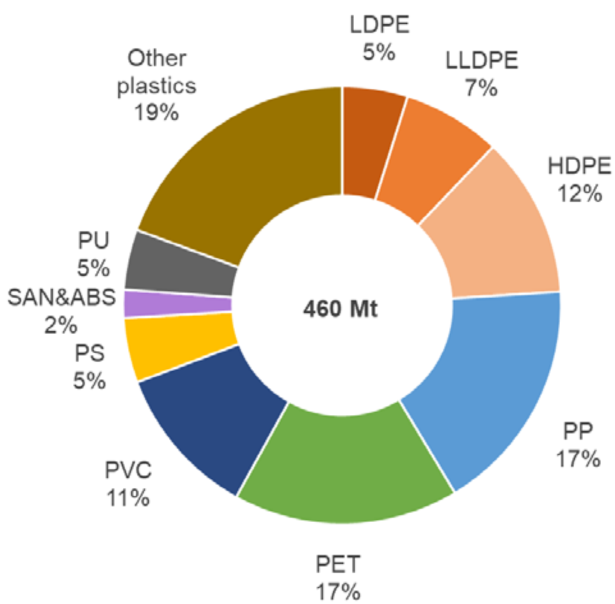

Figure ES- 1. Distribution of global plastic production by plastic polymer in 2019.

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.

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[2] 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.

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 $GtCO_2e$ in 2019, representing 5.3% of total global GHG emissions (excluding agriculture and land use, land-use change and forestry (LULUCF)).[3] 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,

[3] GHG emissions across the plastic polymer value chains are quantified as CO_2-equivalents (CO_2e) 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].

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.

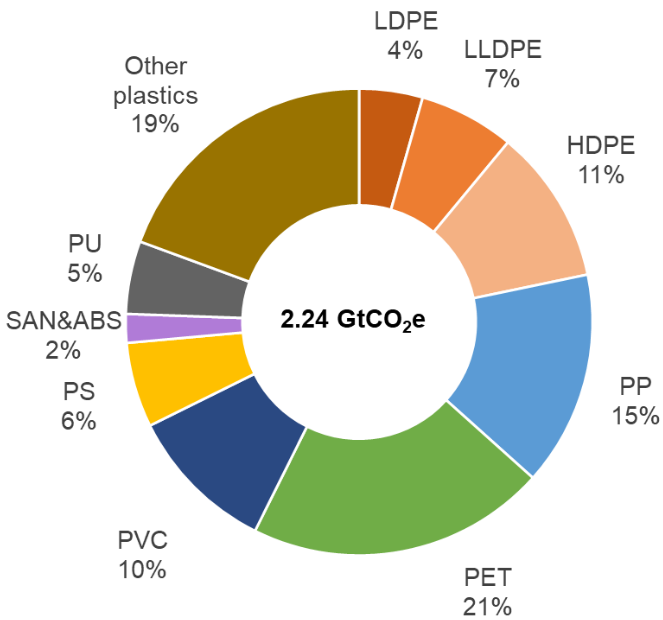

Figure ES- 2. GHG emissions from primary plastic production by plastic polymer type in 2019.

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.

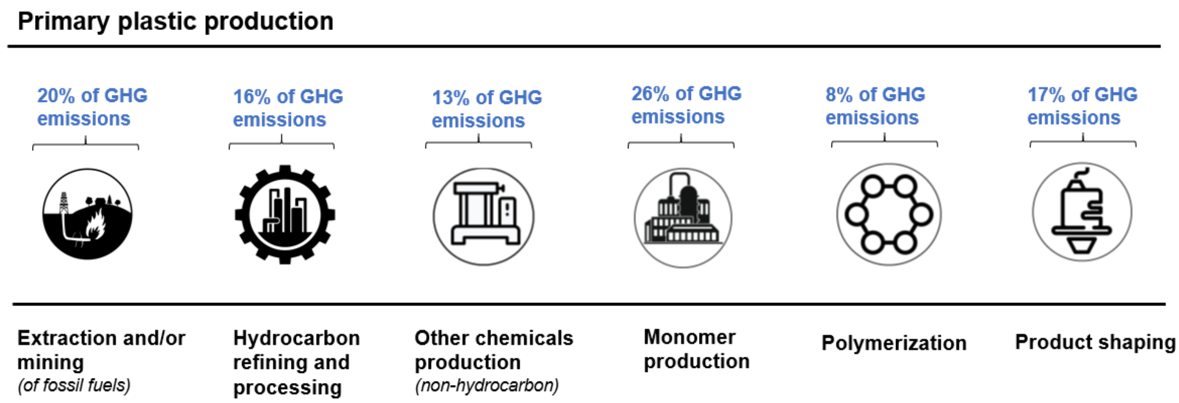

Figure ES- 3. GHG emissions shares of plastic production stages in 2019.

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).[4]
- 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,

[4] 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.

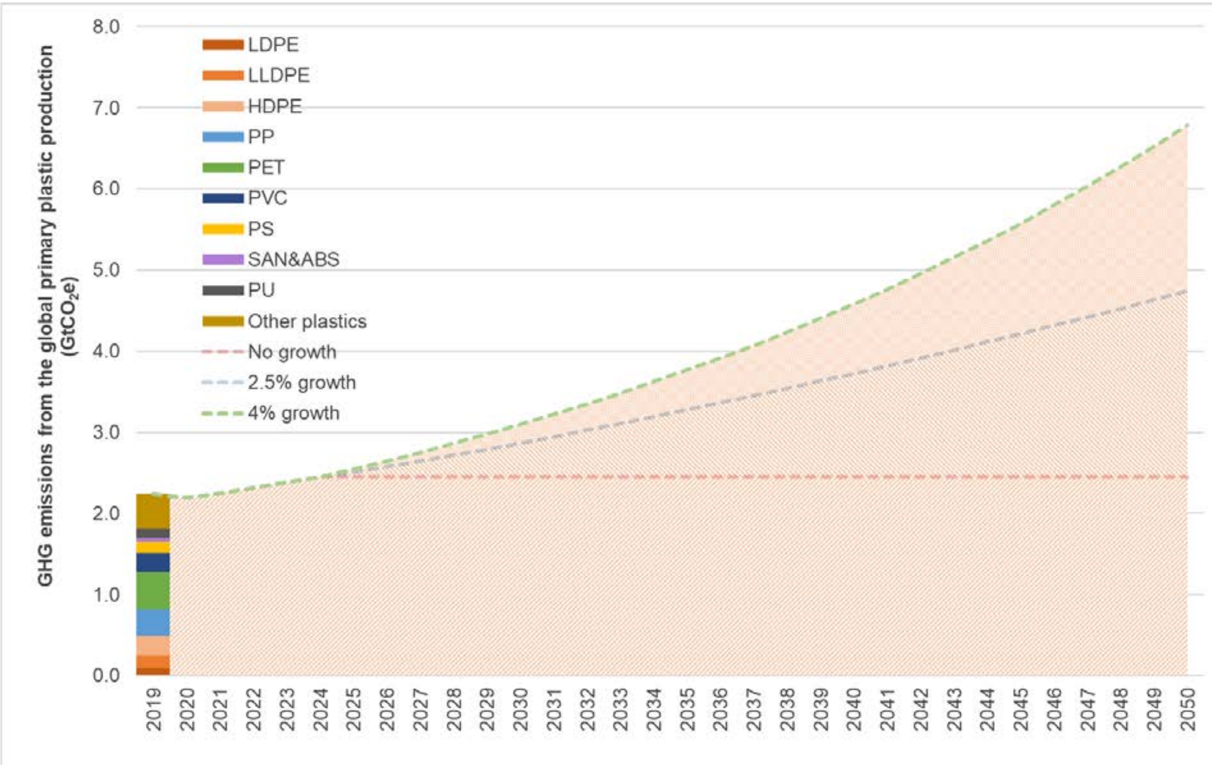

Figure ES- 4. GHG emissions from global primary plastic production between 2019 and 2050 under BAU No growth, 2.5% growth, and 4% growth scenarios.

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 ($GtCO_2e$)	**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 $GtCO_2e$, and for limiting warming to 1.5°C by 2050 with a probability of 67% has been assessed as 400 $GtCO_2e$ [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.[5] 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.[6] 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

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

[6] 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.

References

[1] OECD (2022) Global Plastics Outlook: Policy Scenarios to 2060.

[2] Geyer R., Jambeck, J.R., Law, K.R. (2017) Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782. DOI:10.1126/sciadv.1700782

[3] Solomon, C.G., Salas, R.N. (2024) Health Effects of Fossil Fuel–Derived Endocrine Disruptors. Fossil-Fuel Pollution and Climate Change. N Engl J Med. 390:922-33. DOI: 10.1056/NEJMra2300476

[4] IPCC (Intergovernmental Panel on Climate Change) (2022) Climate Change 2022 Mitigation of Climate Change Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

[5] IRP (2020). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

[6] Rosenboom, JG., Langer, R. & Traverso, G. (2022) Bioplastics for a circular economy. Nat Rev Mater 7, 117–137 (2022). https://doi.org/10.1038/s41578-021-00407-8

[7] Bauer, F., Tilsted, J.P., Pfister, S., Oberschelp, C., Kulionis, V. (2023) Mapping GHG emissions and prospects for renewable energy in the chemical industry, Current Opinion in Chemical Engineering, Volume 39, 100881, ISSN 2211-3398, https://doi.org/10.1016/j.coche.2022.100881

[8] NASEM (National Academies of Sciences, Engineering, and Medicine) (2022) Reckoning with the U.S. Role in Global Ocean Plastic Waste. Washington, DC: The National Academies Press. https://doi.org/10.17226/26132

[9] IEA (2023b) World Energy Outlook 2023. https://iea.blob.core.windows.net/assets/86ede39e-4436-42d7-ba2a-edf61467e070/WorldEnergyOutlook2023.pdf

[10] WRI (World Resources Institute) (2022) World Greenhouse Gas Emissions: 2019. Available from: www.wri.org/data/world-greenhouse-gas-emissions-2019

[11] IEA (2024b) Transport. Available from: https://www.iea.org/energy-system/transport

[12] Schyns, Z.O.G., Shaver, M.P. (2021) Mechanical Recycling of Packaging Plastics: A Review. Macromol. Rapid Commun.2021, 42, 2000415. Special Issue: Polymers for a Sustainable Future.

[13] Rahimi, A., García, J. (2017) Chemical recycling of waste plastics for new materials production. Nat Rev Chem 1, 0046. https://doi.org/10.1038/s41570-017-0046