Modelling plastics in ENV-Linkages

A novel approach to projecting plastics use and waste

TECHNICAL REPORT

BETTER POLICIES FOR BETTER LIVES

Unclassified **English - Or. English**

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A novel approach to projecting future plastics use and waste

This technical document presents a novel approach to modelling and projecting plastic use and waste, relying on the OECD ENV-Linkages computable general equilibrium model. This report also highlights the contribution of the approach to the existing literature on plastics projections and compares the results of ENV-Linkages with those from other studies. This modelling approach was used for the publication of the OECD Global Plastic Outlook (2022).

The report was prepared by Ruben Bibas, Eleonora Mavroeidi, Rob Dellink, Elisa Lanzi, Maarten Dubois, Norbert Monti, Daniel Ostalé Valriberas, Jean Fouré, and Shardul Agrawala, all OECD Environment Directorate.

This report has been produced with the financial assistance of the European Union. The views expressed herein do not necessarily reflect the official views of the OECD or of the governments of its member countries and can in no way be taken to reflect the official opinion of the European Union.

Contact: Elisa Lanzi (elisa.lanzi@oecd.org)

Table of contents

FIGURES

TABLES

Executive Summary

The use of plastics has seen a remarkable increase since the mid-20th century. The increasing use of plastics causes environmental impacts throughout its lifecycle, from the production and use phase, to the end of life phase. As not all waste is properly managed, part of the plastic leakage ends up in rivers and oceans, posing a great threat to the environment.

An increasing number of studies has focused on projecting plastics in the coming decades, with a focus on the amount of plastics that is projected to leak to the environment. Some of these studies describe the lifecycle of plastic commodities in detail, while others use direct links between population or economic growth and plastic waste. What is largely lacking are models that embed details of plastics commodities into a consistent global multi-sectoral macroeconomic framework, better linking economic drivers and plastic projections.

This paper presents a novel approach to plastics projections, which on the OECD's ENV-Linkages computable general equilibrium (CGE) model. The projections with ENV-Linkages differ from previous studies due to the differences in methodology and data sources, such as the assumed drivers of future economic growth. The advantage of this modelling approach is that it takes into account structural and technology changes and is therefore, it is able to capture a much more complex set of economic variables, such as the servitisation of the economy.

The results with ENV-Linkages model are qualitatively similar to the existing literature, alerting to a strong increase in plastics use, waste and leakage, in absence of additional policy action. The ENV-Linkages model projects a tripling of plastic waste generation from 353 Mt in 2019 to 1 014 in 2060. Previous studies have similar results, but often lower amounts of plastic waste, since most existing studies only take into account municipal solid waste while ENV-Linkages also accounts for industrial waste. The results remain nevertheless qualitatively similar: Geyer, Jambeck and Law (2017[2]) project a tripling of total (municipal and industrial) plastic waste by 2050, from 302 Mt in 2015 to 902 Mt in 2050, while Lebreton and Andrady (2019[4]) project a more than doubling of municipal plastic waste, from 181 Mt in 2015 to 380 Mt by 2060, and Lau et al. (2020[6]) predict a doubling of municipal plastic waste from about 220 Mt in 2016 to roughly 420 Mt in 2040.

For mismanaged waste, ENV-Linkages projects an increase from 79 Mt in 2019 to 153 Mt in 2060. Jambeck et al. (2015[1]) project a more than doubling, from 32 Mt in 2010 to 69 Mt by 2025. Lebreton and Andrady (2019[4]) project an almost tripling of mismanaged plastic waste from 80 Mt in 2015 to 213 Mt by 2060. Lau el al. (2020[6]) project a more than doubling from 91 Mt in 2016 to 240 Mt by 2040. The differences stem from the waste projections but also from the approach taken in ENV-Linkages, which assumes progress over time in waste management practices.

Finally, there are differences in plastic leakage projections, which result from differences in previous modelling steps as well as advances in methodologies for the estimation of leakage. Based on the ENV-Linkages plastics use and waste projections, experts have estimate that plastic leakage will double from 22 Mt in 2019 to 44 Mt in 2060, of which 6.1 Mt in 2019 and 11.6 Mt in 2060 leaking to aquatic environments. In the previous literature, Jambeck et al. (2015[1]) estimate an increase from 10.5 Mt in 2020 to 17.5 Mt in 2025. Furthermore, Borelle et al. (2020[5]) estimate that plastics leaked into aquatic environments would be at 43.5 Mt in 2025 and rise up to almost 62 Mt in 2030 while Lau et al. (2020[6]) find that about 81 Mt of plastics will be leaked into the environment in 2040, a more than doubling from 2016 estimates. While the differences in estimates for plastic leakage to the environment are small, those for plastic leakage to aquatic environments are quite large. These large differences are due to a change in the methodology to calculate plastic leakage to aquatic environments, which takes into account the large amounts of time that can be needed for plastics to move around in the environment and reach rivers or the oceans.

Overall, while the ENV-Linkages methodology leads to the qualitative confirmation of existing consensus on the projected growth of plastics use, waste and leakage, the increased granularity and improved methodology provide significant novel insights and more robust quantitative conclusions.

1 Introduction

The use of plastics has seen a remarkable increase since the mid-20th century. Plastics use has reached 460 million tonnes (Mt) in 2019 (OECD, 2022[1]), with significant consequences for the environment. Damages to the environment span the lifecycle of plastics: plastics is produced and used; it then turns to waste, sometimes almost immediately and sometimes after decades. Not all waste is properly managed and some waste is littered so plastics leak to the environment. Part of the plastic leakage ends up in rivers and oceans, posing a great threat to the environment with an estimated 22 Mt of plastics leaked to the environment in 2019 (OECD, 2022[1]).

An increasing number of studies has focused on projecting plastic leakage to the environment in the coming decades.[1] Some of these studies rely on engineering models that describe the lifecycle of plastic commodities in detail, while others use direct links between population or gross domestic product (GDP) and plastic waste. What is largely lacking are models that embed details of plastics commodities into a consistent global multi-sectoral macroeconomic framework, i.e. that represent the heterogeneity in plastics polymers and the economic applications where they are used to provide a detailed correspondence between economic activity and plastics use. Existing studies also pre-date the COVID-19 pandemic and do not account for the disruptions and the potential longer-term implications of the pandemic on plastics use and waste generation (OECD, 2022[1]).[2] Finally, the literature so far does not provide a comprehensive overview of the performance of key levers available to decision makers to curb plastics use.

Existing studies provide a set of projections that all point towards the same conclusion: without additional policies, plastic waste and leakage to the environment are projected to substantially increase in the coming decades. Despite the similarities, there are divergences in projections, which can be attributed to the choice of projection methodology and the drivers used. Geyer, Jambeck and Law (2017[2]) project a tripling of total (municipal and industrial) plastic waste by 2050, from 302 Mt in 2015 to 902 Mt in 2050, while Lebreton and Andrady (2019[4]) project a more than doubling of municipal plastic waste, from 181 Mt in 2015 to 380 Mt by 2060. Lau et al. (2020[6]), also predict a doubling of municipal plastic waste from about 220 Mt in 2016 to roughly 420 Mt in 2040. For mismanaged waste, Jambeck et al. (2015[1]) project a more than doubling, from 31.9 Mt in 2010 to 69 Mt by 2025. Lebreton and Andrady (2019[4]) project an almost tripling of mismanaged plastic waste from 80 Mt in 2015 to 213 Mt by 2060. Lau el al. (2020[6]) project a more than doubling of mismanaged waste, increasing from 91 Mt in 2016 to 240 Mt by 2040. For plastic leakage, projections from Jambeck et al. (2015[1]) put leakage in 2020 at 10.5 Mt and at 17.5 Mt in 2025, a doubling from 2010 estimates. According to projections from Borelle et al. (2020[5]) plastics leaked into aquatic environments would be at 43.5 Mt in 2025 and rise up to almost 62 Mt in 2030, which is a tripling from the 2016 values. Lau et al. (2020[6]) find that about 81 Mt of plastics will be leaked into the environment in 2040, a more than doubling from 2016 estimates.

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[1] Including Jambeck et al. (2015[4]), Geyer, Jambeck and Law (2017[7]), UN Environment (UN Environment, 2018[68]), Lebreton and Andrady (2019[2]), SystemIQ and the Pew Charitable trust (2020[58]), Borelle et al. (2020[44]), Ellen MacArthur Foundation (2017[69]).

[2] Chapter 3 in OECD (2022[1]) presents an analysis of the consequences of the COVID-19 pandemic on plastics use and waste. The projections are also sensitive to other unexpected changes to the global economy, such as the war in Ukraine. The consequences of war in Ukraine on plastics use have not yet been analyse due to lack of data. However, OECD (2022[50]) presents a sensitivity analysis of the projections on plastics use to changes in energy prices.

This paper puts forward a novel framework that focuses in more detail on the socio-economic divers of plastics use in order to obtain projections of plastics use, waste and leakage to the environment. The approach uses a computable general equilibrium (CGE) model as the key tool to create these projections. Specifically, the paper extends the OECD's multi-sectoral, multi-regional dynamic CGE model ENV-Linkages (Chateau, Dellink and Lanzi, 2014[2]) with quantifications of the life cycle of plastics, using links between plastics and economic activity that are polymer-, sector-, region- and time-specific. The paper presents how the model has been extended to include projections of future plastics use, waste and leakage for 14 polymer categories as well as both primary (both produced from fossil fuels and biomass) and secondary (recycled) plastics production.

A strength of CGE models such as ENV-Linkages is that they embed the drivers of sectoral and regional plastics use, such as demand patterns, production modes (including recycling activities) and trade specialisation, into a consistent framework. Compared to projections of plastics use that already exist in the published literature,[3] the approach presented here considers sectoral dynamics, besides economic growth and population growth trends. The modelling approach in this report provides a more accurate link between plastics use and economic activities and a more detailed understanding of the consequences of policy action. It considers plastics not only as a final good for consumption, but, above all, as a production input for each sector, thereby taking into account the complexity of the interactions across sectors and regions and along the plastics lifecycle.

The ENV-Linkages modelling framework can also be used to calculate plastic waste flows. The generation of waste is directly linked to the use of plastics but with a delay that depends on the lifespan of each plastic product. Plastic production data is combined with product lifetime distributions for different use sectors or product categories to model the length of the use phase before they are discarded. The lifespan can be very short, as for packaging, or can span several decades, as for products used in construction (Geyer, Jambeck and Law, 2017[3]). International trade in plastic waste is also modelled, i.e. where plastic waste generated in one country is treated in another. Finally, ENV-Linkages model was enhanced to distinguish the end-of-life fates of plastics, which heavily depend on the waste management capacities and regulations of the location where plastic waste is generated and handled. Five end-of-life fates are modelled: waste can be recycled, incinerated, landfilled (in sanitary landfilling), while the remaining waste is either mismanaged or littered. These projections can also be used to create projections of plastic leakage, based on estimates from external research groups and highlighting uncertainties in plastic leakage projections.[4] ENV-Linkages was thus soft-linked with several models to assess the leakage of plastic to the environment, mostly driven by mismanaged waste.

The remaining of this paper is structured as follows. Section 2 presents an overview of the existing literature on plastic projections. Section 3 outlines the methodology of the OECD ENV-Linkages model to create plastic projections. Based on this new modelling approach, Section 4 presents results on plastics use, waste, mismanaged waste and leakage, for a Baseline scenario without new policies. Finally, Section 5 concludes.

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[3] These include Geyer, Jambeck and Law (2017[3]), Jambeck et al. (2015[6]), Ryberg et al. (2019[4]), Gómez-Sanabria et al. (2018[7]), Ellen Macarthur Foundation (2017[10]), SystemIQ and the Pew Charitable Trust (2020[8]), Borrelle et al. (2020[9]), Lebreton and Andrady (2019[11]).

[4] Collaborators include: 1) experts from the Technical University of Denmark (DTU) who led the research underlying a study by Ryberg et al. (2019[4]); 2) experts from the University of Leeds who contributed to Lau et al. (2020[12]); 3) Laurent Lebreton, who wrote various research papers on plastic waste generation and leakage (Lebreton et al., 2017[13]; Lebreton, Egger and Slat, 2019[14]; Lebreton and Andrady, 2019[11]), and contributed to the leakage estimations in Borrelle et al. (2020[9]); and 4) Nikolaos Evangeliou from the Norwegian Institute for Air Research (NILU), who developed the Evangeliou et al. (2020[16]) article.

2 Review of the literature

Despite the economic importance and environmental impact of plastics, there are only a handful of studies that quantify and project quantities of plastics globally. Jambeck et al. (2015[1]) was the first major study which quantified leakage of plastic waste from coastal zones into the ocean. Following the seminal paper, other studies followed in its footsteps. Geyer, Jambeck and Law (2017[2]) offer global plastic waste estimates derived from production data; Ryberg et al. (2019[3]) use a global model of the plastics value chain to estimate current leakage into the environment. Lebreton and Andrady (2019[4]) provide global estimates of plastic waste generation and mismanagement at spatially disaggregated level while Borrelle et al. (2020[5]) offer global estimates of plastic leakage at a spatially disaggregated level. Lau et al. (2020[6]) present plastic waste and leakage projections to 2040.

This section provides an overview of these studies, focusing on the estimates of plastic waste, mismanaged plastic waste and leakage into the environment, and on the methodologies used to create these estimates. However, comparisons should be viewed in light of the specific scope of the studies. While these studies are all concerned with global quantities of plastics, they differ in their scope, including whether they focus on all plastic waste or municipal waste, or whether they are concerned with all plastic leakage or leakage into aquatic environments, or whether they include man-made fibres or not. Other key differences in methodology will also be highlighted.

2.1. The use of socio-economic and historical data as drivers of future values

Studies in the literature project a substantial increase in the quantities of plastics in the future. Socio-economic projections, including mostly changes in aggregate economic output or in demographics, are considered to be the main drivers of plastic waste and leakage. A doubling or tripling of quantities of plastics are, for the most part, due to the assumed doubling or tripling of the underlying drivers, which tend to be modelled in a very aggregate fashion. The drivers of projected values can be categorised as either based on socio-economic variables (population growth, GDP per capita growth), or on extrapolation of historical waste trends. These methods are in some cases mixed together.

In the study by Jambeck et al. (2015[4]), projections are based on population forecasts from CIESIN (2005[9]) to the year 2020 and 2025. The study does not use economic growth projections, and waste management quality does not improve over time. Lebreton and Andrady (2019[2]) use country-scale population projections from 2015 to 2060 (United Nations, 2015[10]), GDP projections from 2015 up to 2021 (IMF, 2016[11]) and from 2022 to 2060 (OECD, 2014[12]). The projections are made at spatially disaggregated level, thereby capturing the relative distributions of GDP per capita within a country, although these remain static at their base-year levels. Projections in Borrelle et al. (2020[5]) are based on a baseline scenario which assumes that future values of population growth and per capita waste generation rates follow established trajectories (World Bank, 2018[13]). Changes in the share of plastic in municipal solid waste are estimated to increase by a rate of 0-10% per year, with a cap at 35%. Meanwhile, the share of inadequately managed waste remains constant.

Historical trends are extrapolated in some studies. Jambeck et al. (2015[4]) project the growth of the global share of plastic in municipal waste based on historical data from US EPA (2014[14]). Geyer, Jambeck and Law (2017[1]) project plastic production by extrapolating historical production data up to 2050. Waste management rates are also projected via extrapolation. Recycling rates, as well as incineration rates increase by 0.7% per annum. In Lau et al. (2020[3]), projections of plastic waste to 2040 are estimated using year-on-year economic growth rates. Growth rates are calculated at a regional scale, assuming that there is saturation of plastics demand at USD 40 000 per capita income levels, corresponding to 120 kg of plastics per year per capita. These rates are then varied between rural and urban populations.

2.2. Modelling plastic waste generation

Studies in the literature use two main methods to estimate plastic waste: a “bottom-up” and a “top down” approach. Despite the differences in approaches, plastic waste estimates tend to be at least qualitatively consistent across studies. According to Jambeck et al. (2015[1]), 99.5 million tonnes (Mt) of municipal plastic waste were generated in 2010 near coasts. Lebreton and Andrady (2019[4]) estimate that 181 Mt of municipal plastic waste were generated globally in 2015, while according to Ryberg et al. (2019[3]), 161 Mt of municipal plastic waste were generated globally in 2015. Lau et al. (2020[6]) estimate that approximately 220 Mt of municipal plastic waste were generated globally in 2016. Geyer, Jambeck and Law (2017[2]) estimate total (municipal as well as industrial) plastic waste at 302 Mt in 2015.

Bottom-up models use per capita data to estimate aggregate values of plastic waste. In this context, estimates between models may diverge because they use different data sources or because data is missing. When data is missing, data imputation methods and assumptions made about the relationship between independent variables (e.g. demographics, gross domestic product (GDP), levels of economic development) and the dependent variables (municipal plastic waste) can influence model estimates. The initial approach in Jambeck et al. (2015[1]) has a focus on using demographic and municipal solid waste data to estimate plastic waste generation. Baseline values are estimated based on coastal population, country-level per capita municipal solid waste generation, and plastics as a percentage of total municipal solid waste. Other studies quantified plastic waste using a similar approach but incorporated economic variables more explicitly. For instance, Lebreton and Andrady (2019[4]) provides more spatial granularity for plastic waste estimates, mainly achieved by using spatial data for both GDP as well as population. They find that there is a positive correlation between GDP per capita and per capita waste generation levels. The authors use the correlation between GDP per capita and per capita municipal solid waste generation to estimate differing waste generation levels between higher and lower income areas. Other studies also incorporated GDP data more explicitly (Lau et al., 2020[6]; Ryberg et al., 2019[3]; Borrelle et al., 2020[5])

Top-down modelling uses plastic production values to estimate plastic waste, the benefit of which is that total production values create an upper bound to plastic waste estimates. Geyer, Jambeck and Law (2017[2]) take such a top-down approach to estimate current values of plastics production and waste. In order to do so, the authors mainly employ a lifetime distribution method that aims to model the time it takes for a product to be discarded. The authors compile plastics production data from 1950 to 2015, with resin data available for 1950-2015, and fibre data available for 1970-2015. Plastics production is separated into different applications: packaging, consumer and institutional products, textiles, electrical/electronic, transportation, industrial machinery, building and construction. Lifetimes tell the time by which on average a certain type of plastics product becomes waste. These waste figures are aggregated across years and applications to estimate total plastic waste.

In addition, most studies do not explicitly model different waste management technologies. Geyer, Jambeck and Law (2017[2]) present different end-of-life waste management options, including recycling, incineration and discarding of plastics waste. The Lau et al. (2020[6]) model, goes further in modelling end-of-life waste management options, such as sanitary landfills, incineration as well as various recycling technologies (both formal and informal, and within formal, both mechanical and chemical recycling).

2.3. Estimating mismanaged waste and litter

Estimates of mismanaged plastic waste show some more divergence. This is because defining and measuring mismanaged waste and litter is challenging since any waste that leaves the formal waste management system (i.e. collected and then not properly treated), or does not enter it at all (i.e. uncollected), can be considered "mismanaged and littered." Mismanaged waste can be thought of as the fraction of plastic waste that is not disposed of in a sanitary landfill, not recycled, or not incinerated and therefore, susceptible to enter the environment. Similarly, littering is difficult to define and measure as it constitutes "the fraction that falls through the cracks" (Boucher et al., 2020[7]), although many advanced countries have litter collection services that prevent all litter from ending in the environment. Jambeck et al. (2015[1]) find that about 31.9 Mt of plastic waste were mismanaged near coasts in 2010. Lebreton and Andrady (2019[4]) find that 80 Mt of municipal plastic waste were mismanaged in 2015. According to Ryberg et al. (2019[3]) 41 Mt of mismanaged plastic waste were generated in 2015. Finally, Lau et al. (2020[6]) estimate that about 91 Mt of mismanaged plastics waste had been generated in 2016.

Definitions can make a difference. In Jambeck et al. (2015[1]), *inadequately* managed waste is defined as the percentage of dumping in middle and high income countries, while in low income countries it is defined as the percentage of dumping plus percentage of landfilling based on World Bank data (Hoornweg and Bhada-Tata, 2012[8]), while *mismanaged* waste is defined as the sum of inadequately managed waste and littering. As such, this study only takes into account municipal solid waste. Ryberg et al. (2019[3]) also estimate mismanaged municipal plastic waste mainly based on the same World Bank data (Hoornweg and Bhada-Tata, 2012[8]). Borelle et al. (2020[5]) define *inadequate* waste management as the percentage which falls under the category of "open dump," "waterways," "other," or "unaccounted for" according to a more recent World Bank data (2018[9]). This more recent World Bank data (2018[9]) data is also used by Lau et al. (2020[6]). However, in addition to the categories open dump," "waterways," "other," or "unaccounted for", "landfill unspecified" is also treated as mismanagement in low- and middle-income countries – thus extending the definition of what constitutes mismanaged waste. Lau et al. (2020[6]) also explicitly incorporates open burning of plastic waste, an underappreciated waste management issue in many developing countries (Velis and Cook, 2021[10]). Meanwhile, Lebreton and Andrady (2019[4]) use country-level data from the Waste Atlas (2016[10]), an alternative source of data.

On the other hand, littering rates are assumed to be homogeneous across all countries. This ignores differences in the plastic type and waste infrastructure, as well as the urban-rural divide, age, gender, and country-characteristics, which can in reality all significantly alter littering behaviour (Boucher et al., 2019[11]). Littering rates are kept at 1-2%, based on an estimate of littering rate in the United States (Keep America Beautiful, 2009[12]).

2.4. Estimating plastic leakage

The lack of data, empirical measurements and the physical science basis for modelling leakage into the environment makes it especially difficult to estimate plastic leakage accurately, especially in percentage terms. Furthermore, uncertainties compound through the life cycle of plastics. Therefore, divergences in estimates are strongest for plastic leakage. Jambeck et al. (2015[1]) estimate that near coasts, 8 Mt of plastics leaked into marine environments in 2010, and 9.1 Mt leaked in 2015. Ryberg et al. (2019[3]) find that about 9.2 Mt are lost globally to the environment (both terrestrial and aquatic) in 2015. Borelle et al. (2020[5]) estimate that 21 Mt of plastic leaked into aquatic environments in 2016. Lau et al. (2020[6]) find that about 29 Mt of plastics leaked into the environment globally, of which about 18 Mt were lost to terrestrial environments while about 11 Mt were lost to aquatic environments in 2016.

In some studies, globally uniform leakage rates are used. For instance, Jambeck et al. (2015[1]) use globally uniform leakage rates for mismanaged plastic waste entering the ocean. The authors, based on a study of municipalities in the San Francisco Bay area, present 40%, 25% and 15% for high, medium and low leakage rates of mismanaged plastics to marine environments. Ryberg et al. (2019[3]) map out the plastics value chain and for each stage they estimate plastic leakage into the environment. Ryberg et al. (2019[3]) estimate leakage by using loss rate estimates taken from the literature which tend to be globally uniform, with some exceptions, such as estimates of regional microplastics loss rates from cosmetics and personal care products and from wastewater.

In other studies, leakage rates are varied along some dimension (e.g. type of plastic or region). Borelle et al. (2020[5]) estimate leakage rates by considering the distance between the source and aquatic ecosystems where plastic waste reaches waters. The gridded cell data used includes downhill trajectories, and the probability of inadequately managed waste to reach aquatic environments decreases with greater distance to waters. The Lau et al. (2020[6]) model uses multiple main pathways from which plastics can enter the natural environment, such as direct dumping by residents into waterbodies, dumping by waste collection vehicles and transfer from dumping and dumpsites and from open burning. Leakage rates across the various pathways are varied based on the type of plastic (rigid monomaterial, flexible monomaterial, multimaterial). Various microplastics leakage pathways are also conceptualised and elaborated in the Lau et al. (2020[6]) model. Specifically, four sources of microplastics leakage are taken into account, those that originate from tire abrasion, from pellets, textiles, and personal care products.

3 The ENV-Linkages approach

A computable general equilibrium (CGE) model like ENV-Linkages can provide an internally consistent and comprehensive view on production, trade, and use of plastics, as well as plastic waste management and leakage to the environment, so as to create plastic projections. The strength of CGE is their ability to embed the drivers of structural change – such as changes in demand patterns, production modes (including increases in recycling activities) and trade specialisation – in a consistent framework.

Compared to previous work, there are several advantages in using a CGE model. First, a CGE modelling framework has a high-level of granularity and can be adapted to include production of primary plastics and secondary plastics (plastics made from recycled materials). The sectoral details of the model can also be exploited to distinguish several categories of plastic polymers and applications. Second, a CGE model can better reflect recent economic trends, including how plastics use and waste have been affected by the COVID-19 pandemic across sectors and regions, and the potential implications for the years to come. Third, the model takes into account inter-linkages across regions through international trade of goods, including plastic waste.

In order to create plastic projections, the ENV-Linkages model (Chateau, Dellink and Lanzi, 2014[19]) is modified and extended to include plastics in 14 polymer categories, link plastics use to the relevant inputs in economic production of the various sectors, and to calculate plastic waste flows. Furthermore, the modelling framework is enhanced to include both primary and secondary plastics production. The rest of this section describes the ENV-Linkages approach in more detail.

3.1. Modelling plastics use in ENV-Linkages

3.1.1. The economic database

The ENV-Linkages model includes primary and secondary plastics production. While in the original database that the model relies on - the GTAP 10 database (Aguiar et al., 2019[5]) - primary and secondary plastic production are aggregated in the same sector (Rubber and plastic products; rpp), the model allows for the distinction of a technology producing primary plastic and an alternative technology producing secondary plastics.

These two technologies produce a similar plastic good. The production of plastic goods is split with two data sources. First, the total shares in production for primary and secondary plastics is taken from the volumes in tonnes described above (Ryberg et al. (2019[18]) for primary and own estimates for secondary plastics). Furthermore, the Exiobase 3 database (Stadler et al., 2018[8]) is used to adapt the cost structures. The main difference stem from the material inputs: the primary technology uses fossil fuels, while the secondary technology uses inputs from the chemical sector.

ENV-Linkages also includes data on plastic volumes in Million tonnes (Mt). Specifically, data on plastics volumes by application and polymer are linked to the detailed sectoral production structure of the model and the GTAP database that underlies the model. This is done for 14 polymer categories (Table 3.1).

Table 3.1. The large range of polymers allows for a multitude of plastics applications

Polymer	Abbreviation	Examples of use
Polypropylene	PP	Food packaging, automotive parts
Low-density polyethylene	LDPE	Reusable bags, food packaging film
High-density polyethylene	HDPE	Toys, shampoo bottles, pipes
Polyvinylchloride	PVC	Window frames, floor covering, pipes, cable insulation
Polystyrene	PS	Food packaging, insulation, electronic equipment
Polyethylene terephthalate	PET	Beverage bottles
Polyurethane	PUR	Insulation, mattresses
ABS, elastomers, biobased plastics, PBT, PC, PMMA, PTFE, …	Other	Tyres, packaging, electronics, automotive, …
Fibres made of different polymers	Fibres	Textile applications but also in many other sectors

Note: ABS stands for Acrylonitrile butadiene styrene, PBT for Polybutylene terephthalate, PC for Polycarbonates, PMMA for Poly (methyl methacrylate) (also known as plexiglas) and PFTE for Polytetrafluoroethylene.

3.1.2. Data on primary and secondary plastics

Volumes of primary plastics for 2015 rely on data from Ryberg at al. (2019[18]), that updates and expands on the seminal work by Geyer, Jambeck and Law (2017[14]). Since the estimates provided by Ryberg et al. (2019[18]) are either by region and application or by application and polymers, an assumption of homogeneity of polymers by application is taken to estimate the primary plastics use by region, polymer and application.

Secondary plastics volumes for 2015 are estimated following a methodology deriving secondary plastics through waste collected for recycling and recycling losses, relying on inputs from the University of Leeds based on a review of the literature.

The estimates for 2019 are based on the 2015 year, using the link between plastics volumes in Mt and plastic inputs to sectors in USD, as described below. In addition, these are complemented with plastics use for the past between 1950 and 2014, for two reasons. The first reason is to be able to accurately compute waste flows in the future, since plastic lifespans can span up to decades. The second reason is to form the basis for the computation of environmental impacts, as for instance plastic leaked in the ocean accumulates over time.

The 1950-2014 historical plastics use, which is necessary for the following step of calculating plastic waste, is calculated following a stepwise approach. First, global plastics use is taken from the Geyer, Jambeck and Law (2017[22]) study. The regional split of plastics use is then based on weight-based estimates of waste, from a cross country regression of municipal solid waste on GDP per capita using What a Waste 2.0 (Kaza et al., 2018[15]), multiplied by the regional consumption shares in 2015. Finally, for each region, the split by polymer and application is assumed to be constant prior to 2014, based on the estimates from Ryberg et al. (2019[18]). This methodology is constrained by data availability (and thus necessarily imperfect) but provides estimates of plastics use by region, polymer and application.

3.1.3. Matching economic data with data on plastic volumes

The two main sources of data (volumes of plastics and economic flows described above) are connected in ENV-Linkages: (i) plastics production and consumption by economic sector by GTAP10 adapted with a primary and secondary production technology in monetary values, and (ii) regional flows of a range of plastic polymers and application-specific flows of plastics in tonnes. Table 3.2 summarises the mapping of the economic sectors and plastics applications. The initial values for this mapping are calibrated using data from (Ryberg et al., 2019[18]), combining polymer distribution by application at the global level with distribution of total plastics use by region and application. The polymer distribution was taken from the global averages and applied for each region taking into account the specific economic structures of the various regions.

Table 3.2. Mapping of plastics use by application to economic sectors

Input sectors	Applications	Output sectors	Polymers
Plastic products	Building & Construction	Construction	ABS, ASA, SAN; Bioplastics; HDPE; LDPE, LLDPE; PP; PS; PUR; PVC; Other
	Consumer & Institutional products	Accommodation and food service activities; Air transport; Education; Health; Insurance; Lumber; Non-metallic minerals; Business services; Other manufacturing; Public services; Land transport; Pulp, paper and publishing; Real estate; Textile; Water transport	ABS, ASA, SAN; Bioplastics; HDPE; LDPE, LLDPE; PP; PS; PUR; PVC; Other
	Electrical/Electronic	Electrical equipment; electronics	ABS, ASA, SAN; Bioplastics; HDPE; LDPE, LLDPE; PP; PS; PUR; PVC; Other
	Industrial/Machinery	Fabricated metal products; iron and steel; nonferrous metal; Machinery and equipment	HDPE; LDPE, LLDPE; PP; PUR
	Packaging	Food products; Chemical products	Bioplastics; HDPE; LDPE, LLDPE; PET; PP; PS; PUR; PVC; Other
	Personal care products	Chemical products	HDPE; PET
	Transportation - other	Motor vehicles; Public services; Other transport equipment	ABS, ASA, SAN; Bioplastics; Fibres; HDPE; LDPE, LLDPE; PP; PUR; PVC; Other
	Other	Other sectors	Other
Chemicals	Marine coatings	Other manufacturing, other transport equipment	Marine coatings
	Road markings	Construction	Road markings
	Textile sector - clothing	Textiles	Bioplastics; fibres
	Textile sector - other	Textiles	Fibres
	Transportation - tyres	Plastic products	Elastomers (tyres)

Source: OECD ENV-Linkages model.

Based on the initial picture in 2015, primary plastics use is projected following the flows of “plastics products” into the various corresponding demand sectors, from initial values, following the methodology developed for the OECD’s Global Material Resources Outlook (OECD, 2019[4]). In particular, the model incorporates a series of plastics chains from initial production to final demand, either partially or in full depending on the particular structure of each regional economy. The basis for the chain includes flows from “oil” or “biomass” to “chemicals”, which are then used for the production of “plastic products” which serve as intermediate goods or for sectors such as food product/appliances/motor vehicles/construction, before reaching final demand. The underlying assumption is that the coefficient (tonne/USD per polymer, per application, per region) that links monetary flows to physical flows (in tonnes), is kept constant. Plastics production then follows these demands, based on trade flows and plastics use.

There are three steps to project plastics use and the split of primary and secondary plastics to fulfil demand in baseline projections. First, total demand for plastics use is estimated following the evolution of the demand for the plastic commodity (produced by both the primary and secondary technologies). Second, the tonnes of secondary plastics, i.e. the volume of plastics produced by the secondary technology, follow the growth of the secondary sector in the ENV-Linkages projections, reflecting that collected, sorted and reprocessed materials (further referred to as plastic scrap) are – after correcting for loss rates (see Annex A) - generally fully used to produce secondary plastics. Third, the volumes of primary plastics are calculated as a residual between the two. This is fully consistent as both technologies are perfect substitutes, the coefficients that link monetary and physical flows are constant and the total volume of production using primary and secondary technologies matches total demand for plastics.

Box 3.1. Losses from sorting and reprocessing

Plastic waste that has been collected for recycling almost always includes some non-plastic materials and articles. Moreover, collected plastic waste typically includes a multitude of plastics with varying chemical and physical composition. The degree to which these items, objects and fragments are useful to a plastics reprocessor depends on wide range of factors that influence the value of the material. In general, high-income countries implement recyclate collection schemes (programmes) that are designed to yield high material mass through an accessible and simplified system that is easy for people to understand. Conversely, in low- and middle-income countries, plastic waste collection for recycling is carried out by informal workers (IRS) who selectively collect (cherry pick) items and objects that are most valuable, focusing on quality and concentration rather than high yield. Even with diligent, selective collection, plastic articles contain a multitude of intentionally and non-intentionally appended, entrapped, adhered and entrained materials and objects that must be removed from the dominant plastic before it can be most often comminuted and remelted under pressure in an extruder. A list of characteristics of waste plastics and their influence on the value of materials and hence their recyclability is reported by Cottom et al. (2022[10]).

Robust and generalisable loss rates during sorting and reprocessing for plastic waste that has been collected for recycling are not commonly reported. Hestin, Faninger and Milios (2015[23]) proffered 18% and 30% for sorting and reprocessing respectively, based on surveys of European reprocessors. However, the nature of the survey was not reported and it is possible that plastic and non-plastic material and objects may have been reported alongside plastic losses. The ENV-Linkages model is only concerned with plastic so data for non-plastic were excluded from this component of the model.

A theoretical model based on material value was developed by the University of Leeds for plastic waste collected for recycling in high-income countries and low- and middle-income countries. Acknowledging that collection and sorting systems vary enormously worldwide, these two generalised groups were chosen because high income countries largely operate, either single stream collection of dry recyclate or co-collection of mixed plastic waste alongside metal packaging. Conversely in low-income and middle-income countries, collection of plastic waste for recycling is largely carried out by the informal recycling sector whose participants selectively collect materials and have much lower loss rates.

3.2. Modelling plastic waste and end-of-life fates in ENV-Linkages

Plastic waste can be calculated in ENV-Linkages linking plastic use to the lifespan distribution of different products. Waste is calculated as a function of plastics use (in volumes), following Geyer, Jambeck and Law (2017[22]), using a methodology based on lifespan distributions,[5] under the assumption of global homogeneity.[6]

Plastic waste of different applications are grouped into three main categories: Municipal Solid Waste (MSW), Other and Markings & Microbeads. MSW includes packaging, consumer & institutional products, electrical/electronic and textiles. 'Other' incorporates waste that is not included in MSW, therefore mostly

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[5] As it is not possible to use lifespan distributions from historical years, in the first years an exogenous component of waste generated by earlier produced commodities is added.

[6] Due to lack of country/application specific lifespan data.

reflecting waste from industrial applications (including building and construction, industrial and machinery applications, transportation applications). Markings & Microbeads include marine coatings, road markings and personal care products.

3.2.1. End-of-Life Fates

Plastic waste is divided into different waste management streams (end-of-life fates) by applying end-of-life shares that vary across countries, polymers and waste categories. MSW and industrial plastic waste categories can be: (i) recycled, (ii) incinerated or (iii) discarded. The latter is further disaggregated into waste that is disposed of in sanitary landfills, and the remainder, i.e. mismanaged waste. Littering is treated separately: part of the litter is collected and then treated in the same way as other collected waste, while uncollected litter is included with mismanaged waste.[7] It is set as a constant share of municipal solid waste following the assumption in Jambeck et al. (2015[17]). A final category of plastic waste is markings & microbeads; these form a very small stream (by mass) that is assumed not to be managed and to leak directly to the environment.

The sources of end-of-life fate shares for the base year, 2019, vary across regions. Recycling (defined here as material that has been collected for recycling) shares for plastics are exogenously fixed – but evolving over time – based on a range of sources, primarily country sources (Table 3.3). Notably, for the EU the recycling rate reported by Plastics Europe (2020[33]) was adjusted to ensure that polymer specific recycling rates are within the range of the EU plastics packaging recycling rates. For China, the official recycling rate in 2017 was used (Ministry of Commerce, 2019[34]). Recycling rates for other non-OECD regions were based on estimates of MSW recycling rates from What a Waste 2.0 (Kaza et al., 2018[15]) and consultations with experts. For the Middle East & North Africa, Other Africa, Other Eurasia and Latin America regions, projections were adjusted to account for informal recycling that is not reported but typically recovers high value streams such as HDPE and PET bottles.

The recycling shares are further split across polymers by multiplying the recycling shares for plastics by factors that reflect the recyclability and value of individual polymers based on expert consultations and ensuring that the estimated recycled volumes do not exceed the recycling capacities subject to data availability. Overall, PET and HDPE are assumed to have the highest recycling rates, followed by LDPE, PP and PVC (for construction). PUR, fibres, elastomers, bioplastics, marine coatings and road markings are not recycled, while only a very small proportion of PS, ABS, ASA, SAN and other polymers can be recycled.

To account for unreported informal recycling (which leads to understating plastic recycling rates) or overly optimistic reported recycling rates, all reported recycling rates were sense-tested, adapted and validated leveraging on consultations with experts and modelling carried out by Ed Cook, Josh Cottom and Costas Velis from the University of Leeds.

The use of incineration as a waste treatment type is country-specific and related to historic elements and local population densities. The share of plastic waste that is incinerated is strongly correlated with the share of total solid waste that is incinerated. Therefore, the incineration shares are set so that the ratio of the incineration share to the non-recycled share is equal to the corresponding ratio for total MSW from the What a waste 2.0 database (Kaza et al., 2018[15]). Moreover, the same incineration shares apply for non-MSW plastic waste.

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[7] Littering including both collected and uncollected littering, is set as a share of municipal solid waste following the assumption in (Jambeck et al., 2015[17]).

Table 3.3. Data sources for plastic recycling rates in base year

Region	Recycling Rate Source and Assumptions
USA	United States Envrionmental Protection Agency (EPA) (2020[35]; 2020[36])
Canada	Environment and Climate Change Canada (2019[37]) *
Other OECD America	Based on SEMARNAT (2020[38]) and FCH (2021[39])
OECD EU countries	Polymer-specific recycling rates have been determined based on expert opinion and applied to the volumes of polymers collected for recycling by ENV-Linkages.**
Other EU	
OECD Non-EU countries	Based on EU adjusted by the proportion of region's MSW recycling rate to EU MSW recycling rate from What a Waste 2.0 (Kaza et al., 2018[15])
OECD Asia	Plastic Waste Management Institute (2019[40]) and expert judgement to account for recycling rates in Korea
OECD Oceania	Australian Government (2020[41]) ***
Latin America	Based on Other OECD America adjusted to account for a larger informal sector
Other Eurasia	What a Waste 2.0 (Kaza et al., 2018[15])
Middle East & North Africa	What a Waste 2.0 (Kaza et al., 2018[15])
Other Africa	What a Waste 2.0 (Kaza et al., 2018[15])
China	China Recycling Industry Development Report (2013-2018) by the Ministry of Commerce (2019[34])
India	Central Pollution Control Board (2019[42]) and UNIDO (2020[43])
Other non-OECD Asia	What a Waste 2.0 (Kaza et al., 2018[15])

* An updated report is available: (Statistics Canada, 2022[44]).
** For the EU, the calculated recycling rate for total plastics has been benchmarked with the numbers presented by Plastics Europe (2020[33]). In ENV-Linkages, the total amount of plastics collected for recycling is slightly higher (the numerator of the recycling rate), while the amount of plastics taken into account for the calculation is substantially higher (the denominator: total plastics includes fibres and other rarely recycled plastics). So the total recycling rate of plastics in ENV-Linkages is lower than Plastics Europe (2020[33]).
*** An updated report is available: Government of Australia (2021[45]).

Discarded waste equals all collected waste that is not collected for recycling or incinerated. This discarded share is split into sanitary landfilling and mismanaged waste. Thus, mismanaged waste includes open dumping and unaccounted waste treatments for all income levels apart from lower and lower middle income countries, for which also unspecified landfilling, waterway treatment and other categories are included. The data on mismanaged waste are based on country level data for MSW (Kaza et al., 2018[15]) and build on assumptions adopted in Jambeck et al. (2015[29]) for the previous version of the database in In general, mismanaged plastic waste as a share of total plastic waste is expected to decrease with income level, i.e. the share of sanitary landfilling increases with income. Following this assumption and using MSW data from (Kaza et al., 2018[15]), the share of mismanaged plastic waste was estimated by regressing the ratio of mismanaged waste to discarded waste on GDP per capita, accounting for regulatory differences between OECD and non-OECD countries using an OECD dummy. Specifically, the following regression was estimated for 156 countries for which complete data was available:

$$\frac{MIS_i}{MIS_i + LAN_i} = \alpha - \beta * ln\left(gdp_{pc_i}\right) + \gamma * OECD_i$$

where MIS_i = mismanaged waste/MSW, LAN_i = Landfilled waste/MSW, gdp_pc_i = GDP per capita and $OECD_i$ = dummy for OECD countries, i = country. Finally, the share for landfilled waste is equal to the residual.

Historical data for recycling, incineration and discarded shares of plastic waste are taken from Geyer, Jambeck and Law (2017[22]) for the period 1980-1990 for four regions – United States, EU, China and Rest of the World. Following, using granular data for MSW recycling and incineration rates from Kaza et al. (2018[15]), the historical shares for 1990 were mapped to the 15 regions within ENV-Linkages, and were linearly interpolated for the period 1990-2018 in line with the methodology previously applied in Geyer, Jambeck and Law (2017[22]). Historical data for mismanaged and landfilling following the same methodology as in the base year.

3.2.2. Modelling international trade in plastic waste

The ENV-Linkages model has been extended to include inter-regional trade in plastic waste per application and polymer type. Volumes of plastic waste exports and imports are calculated based on data from UN Comtrade (United Nations Statistics Division, 2020[46]) following two steps. First, total exports of plastic waste per country and polymer are estimated using the share of plastics exports (Comtrade) to plastic waste (output of ENV-Linkages). Second, exports are split into partner countries and polymers using the country and polymer weights in 2019 for projections, and historical data for the years before. Bilateral exports and imports weights per country (row weights) were calculated based on the bilateral data on exports and imports values for the period 2010-2019 (most recent and complete year) and for the four subcategories of plastic waste reported in the UN Comtrade database. The latter were mapped to the polymer types included in ENV-Linkages (Table 3.4). To ensure that global trade balances, bilateral plastic waste imports per reporter-partner pair correspond to the bilateral export of the corresponding partner-reporter pair. Note that trade flows between countries that are grouped in a single region in the modelling framework are subsumed in the intra-regional accounting and thus excluded from inter-regional trade flows. Consequently, total trade flows in the model are around one-third lower than trade flows based on national data.

The end-of-life fates of plastic waste traded flows differ from the domestically treated waste to reflect the fact a high proportion of traded plastic waste tends to be recyclable. In particular, 50% of traded plastic waste is expected to be recycled, with the remaining being distributed across the other waste streams following the same proportions of end-of-life fates as domestically treated waste.

Table 3.4. UN Comtrade plastic waste series mapping to polymers in ENV-Linkages

UN Comtrade code	Series Description	Polymers types in ENV-Linkages
3915	Waste, parings and scrap, of plastics	
391510	of polymers of ethylene	HDPE, LDPE, LLDPE, PET, PP, PUR, Elastomers (tyres)
391530	of polymers of styrene	PS
391530	of polymers of vinyl chloride	PVC
391590	of other	Fibres, Marine coatings, Road marking coatings, ABS, ASA, SAN, Other

Source: United Nations Statistics Division (2020[46]) and OECD ENV-Linkages.

Linking to external models to estimate plastic leakage to the environment

While ENV-Linkages was enhanced to calculate plastics use, waste and waste management, it is not easy to include also the modelling leakage to the environment. Given the existing literature (Section 2), the best way to estimate plastic leakage is to work with experts on the field:

- experts from the Technical University of Denmark (DTU), who led the research underlying the Ryberg et al. (2019[11]) study, quantified plastic leakage to the environment;
- experts from the University of Leeds, who contributed to Lau et al. (2020[12]), quantified macroplastic leakage to terrestrial and aquatic environments;
- Laurent Lebreton, who contributed to the leakage estimations in Borrelle et al. (2020[13]), quantified plastic leakage to and mobility of plastics in aquatic environments.

The estimates for plastic leakage to the environment can be derived combining the estimates from DTU and Leeds University and providing a range (low, central and high estimates). DTU provides estimates for macroplastic leakage coming from mismanaged waste (municipal solid waste or MSW, non-MSW and litter) and marine activities, as well as microplastics. Leeds University provides estimates for leakage from mismanaged waste only. For mismanaged waste (representing the bulk of the leakage), the central estimates are calculated as the average of the two estimates provided by DTU and Leeds University. High and low then correspond to the higher and lower values between the values produced by DTU and Leeds University. For the leakage of marine activities and microplastics, the values of DTU are used as central estimates.

Aquatic leakage is quantified based on the central projection. To account for uncertainties in estimating emissions at regional level, confidence intervals are given with low and high emission probability ranges derived from the midpoint emission estimate and respectively subtracting and adding the standard deviations of lower and higher country-scale emission probabilities as provided by Borrelle et al. (2020[13]) and weighted by country population size.

Although the combination of approaches draws on state-of-the-art expertise on this topic, the results should be interpreted with care as there is still significant uncertainty surrounding certain parameters used in the modelling.

4 Overview of results

The projections of plastics use with the ENV-Linkages model are therefore detailed by region, polymer and application, and distinguishing between primary and secondary plastics. This section provides an overview of the ENV-Linkages projections on plastics use, waste and leakage, drawing on the OECD Global Plastics Outlook (OECD, 2022[46]).

4.1. Projections of plastics use

4.1.1. Plastic use by region

Plastics use is projected to triple globally from 460 Mt in 2019 to 1 231 Mt in 2060, increasing in all regions. The regional contribution to global plastics use has changed enormously over the last century and is projected to continue changing to 2060 (Figure 4.1). In 1980, OECD countries together accounted for 87% of global plastics use, while Middle East and North Africa and Sub-Saharan Africa ("Other Africa")[8] together accounted for 5%; fast-growing emerging economies in Asia (The People's Republic of China, India and "Other Asia") accounted for only 1% of global plastics use. In 2019, OECD and non-OECD countries contributed almost equally to global plastics use, with the OECD accounting for 46%. China, India and other fast-growing emerging economies in Asia accounted for 35% of global plastics use (China accounting for 20% and India 6%).

Between 2019 and 2060, non-OECD countries are projected to triple their plastics use and, by 2060, will account for 64% of global plastics use. Non-OECD countries in Asia alone will account for 41% of global plastics use in 2060. China remains the region with the highest share in global plastics use, even though its share slightly declines to 17% as the growth in plastics use in the country is lower than the global average growth in plastics use. Plastics use in India is projected to be more than five times larger in 2060 compared to 2019, with its share in global plastics increasing to 13%. Similarly, plastics use increases substantially in other emerging economies in Asia (Other non-OECD Asia). The largest increase in plastics use takes place in Sub-Saharan Africa, where plastics use is more than six times larger in 2060 compared to 2019. Strong population growth in Sub-Saharan Africa, combined with significant income growth, contributes to the projected rapid increase of plastics use in that region.

While their share of global plastics use declines, plastics use is projected to double in OECD countries, as well as in the non-OECD regions not mentioned above, which include Latin American and Eurasian countries. In these regions, moderate growth in income and low population growth, combined with minor structural change, limits the growth of plastics use.

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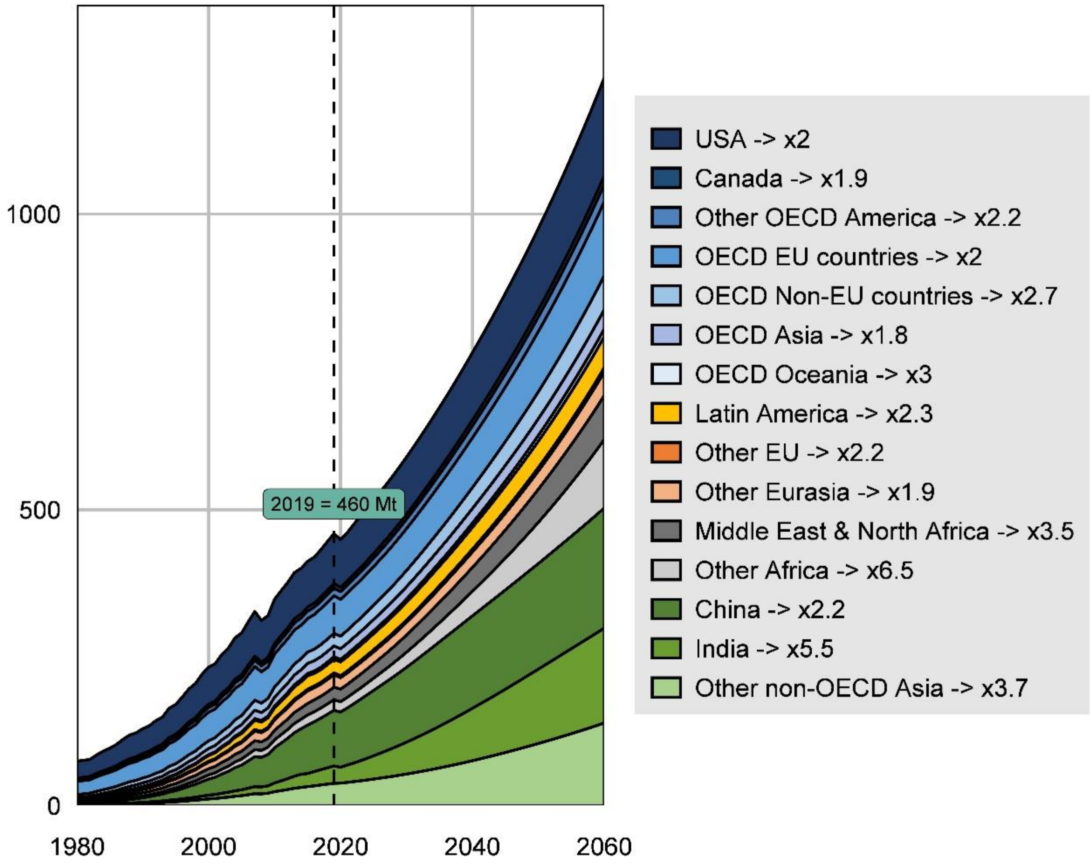
[8] Table A A.2 in Annex A explains the regional groupings used in ENV-Linkages.

Figure 4.1. Plastics use will grow fastest in developing and emerging economies in Africa and Asia

Plastics use in million tonnes (Mt), *Baseline* scenario



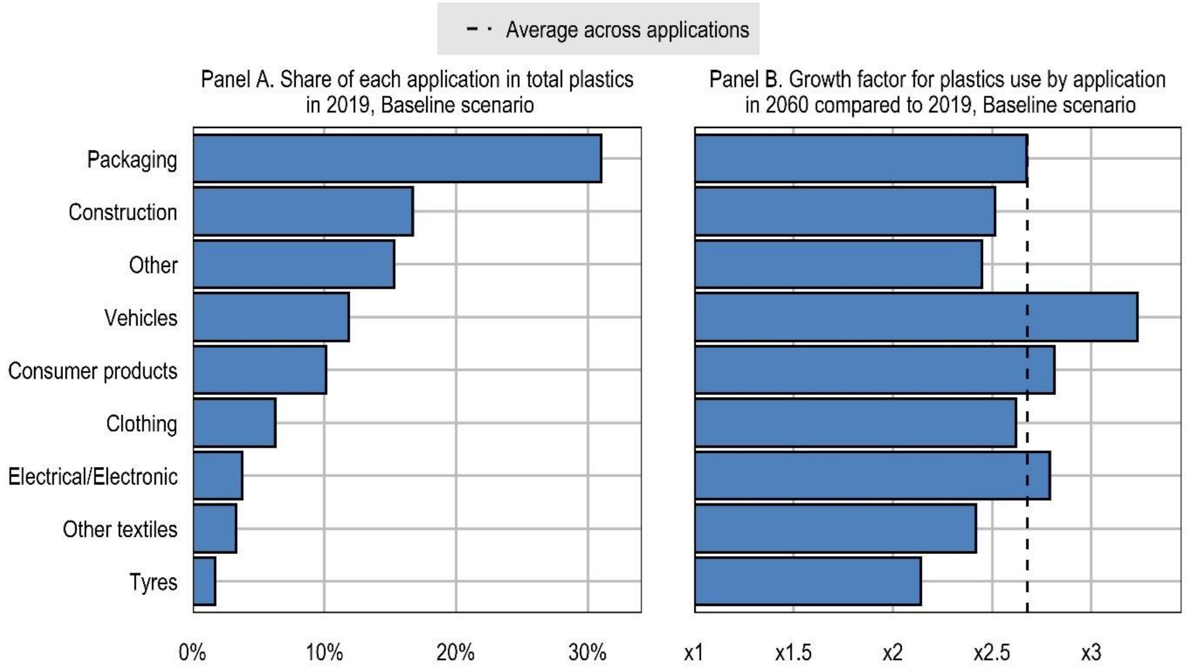
Note: The numbers on the right handside of the graph indicate the growth of plastics use from 2019 (dashed line) to 2060 for each region (e.g. x2 means a doubling of plastics use). Please see Table A A.2 in Annex A for more details on the regional aggregation of the ENV-Linkages model.
Source: OECD ENV-Linkages model.

4.1.2. Plastic use by application and polymer

The advantage of using a computable general equilibrium model is that plastic can be projected by application and polymer, exploiting the sectoral structure of the model, as ENV-Linkages maps plastics use by polymer and application to the model sectors. For instance, as PVC (polyvinyl chloride) is mostly used for construction applications, it is linked to the construction sector in the model, while PP (polypropylene) is used for packaging, amongst other applications, and is linked to several sectors, including food products and business services. In general, polymers are used for multiple applications, and applications are also linked to multiple economic sectors, unless they are highly specialised, such as in construction.

By 2060, plastics use is projected to increase for all applications (Figure 4.2). Plastics use for the production of vehicles increases most, reflecting a rising demand for transport equipment as economies develop. Increasing digitalisation and electrification also sees plastics use increase for electrical and electronic products. While the services sectors have a relatively low plastics intensity (the amount of plastic per unit of output), the servitisation of economies will mean that the services sector will account for the largest share of plastics use. This is reflected in the increase of plastic products frequently used in service sectors, such as packaging and consumer products (e.g. takeaway food containers, health care and medical products, art supplies, credit cards and luggage). The increase in plastics use for packaging shows that policies currently in place are not sufficient to offset the increase in plastics use by key sectors that rely on packaging, including business services, food products and trade.

Figure 4.2. Plastics use in the transport sector will grow the most by 2060

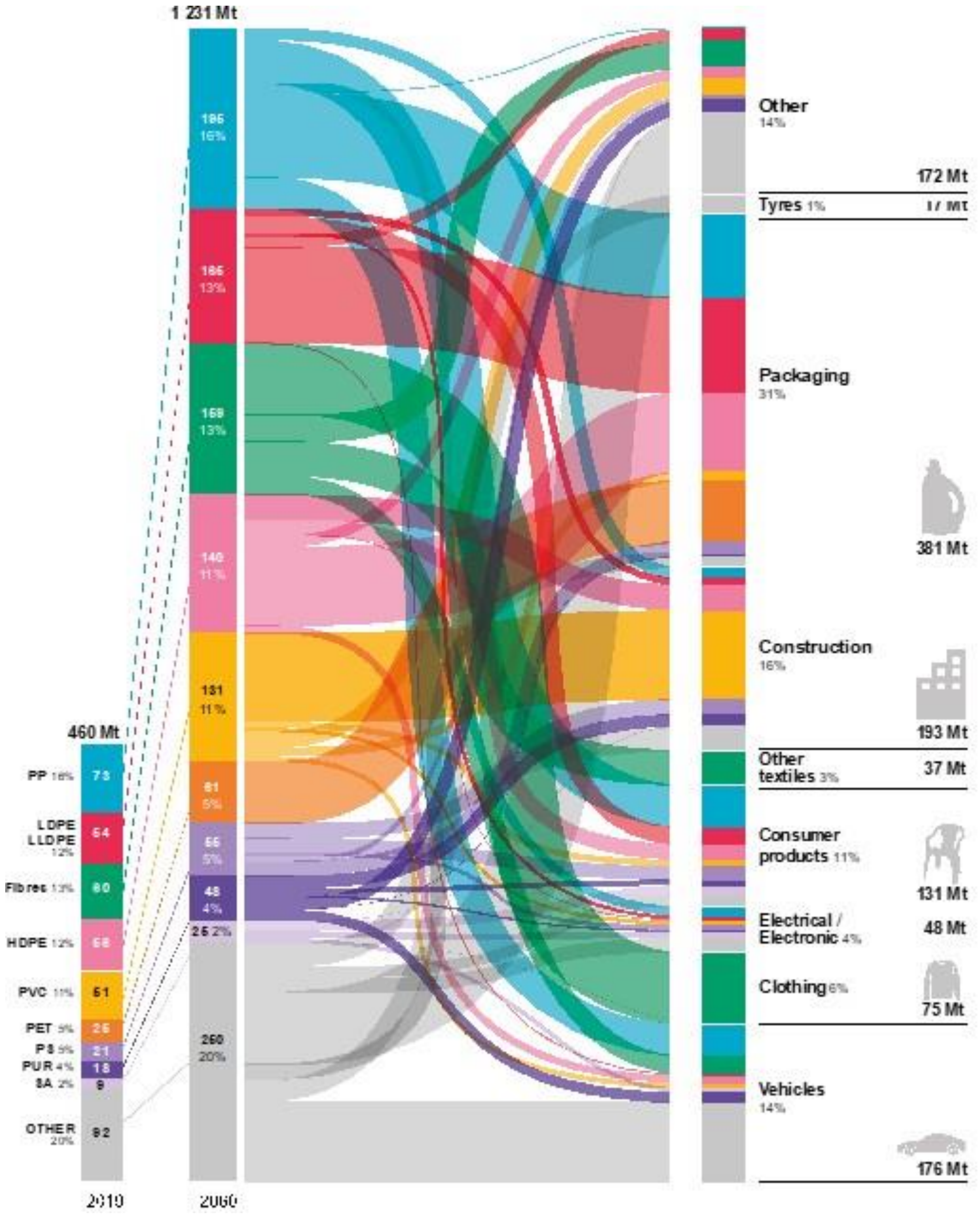


Note: The applications for personal protective equipment linked to COVID-19, and personal care products, are omitted from the graph as the quantity of plastics they use is too small for the calculation to be meaningful.
Source: OECD ENV-Linkages model.

Plastics use is also projected to increase for all polymers (Figure 4.3), as inputs for the different applications also increase. The links between the different polymers and applications is quite intricate, as the same polymers can be used in different ways in various applications, and some polymers actually represent a wide range of different plastics that are grouped in one category because they share certain characteristics. By 2060, there is projected to be a substantial increase in the use of polymers for packaging. Notably, low-density polyethylene (LDPE, and including linear low-density polyethylene or LLDPE) used in packaging triples compared to 2019; while polypropylene (PP), high density polyethylene (HDPE) and polyethylene terephthalate (PET), all used in packaging, more than double. Polyvinyl chloride (PVC), which is used in construction, increases by 2.6 times. Likewise, fibres, which are used for textiles, are projected to triple. The use of polymers for the production of vehicles, and especially PP, is also projected to increase substantially.

Figure 4.3. The use of all polymers will increase to 2060

Increase in plastics use by polymer and application in million tonnes (Mt) *Baseline* scenario, 2019-60



Notes: HDPE = high-density polyethylene; LDPE = low-density polyethylene; LLDPE = linear low-density polyethylene; PET = polyethylene terephthalate; PP = polypropylene; PS = polystyrene; PUR = polyurethane; PVC = polyvinyl chloride; SA stands for ABS, ASA, SAN, where ABS = acrylonitrile butadiene styrene; ASA = acrylonitrile styrene acrylate; SAN = styrene acrylonitrile.

The figure does not include the application personal protective equipment (face masks and other protection linked to the COVID-19 pandemic) as its use was negligible in 2019.

Source: OECD ENV-Linkages model.

4.1.3. Primary and secondary plastics

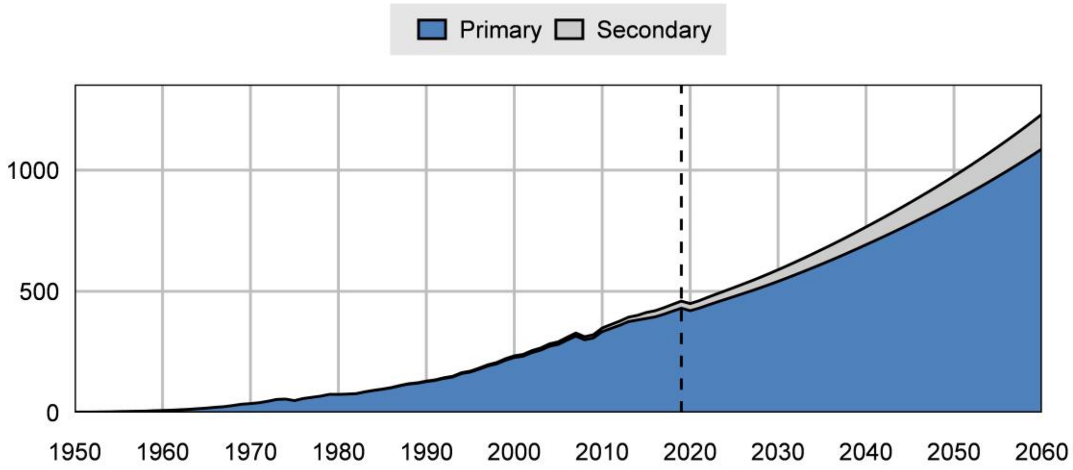
The ENV-Linkages model splits plastics production and use into primary and secondary plastics. Primary plastics include both fossil-based and biobased plastics, which are a rather small group of plastics with similar characteristics to fossil-based plastics, but are derived from biomass such as corn, sugarcane, wheat or residues from other processes. The estimates for secondary plastics are based on available data on plastics labelled for recycling (i.e. that have labels indicating that they can be recycled). They also take into account losses in the process, such as when plastics are collected for recycling, but cannot be recycled.[9]

In the *Baseline* scenario, the growth in global output of primary and secondary plastics production is similar, with secondary plastics production growing slightly faster than primary. The share of secondary plastics, a key indicator of circularity, is projected to double from 6% to 12% between 2019 and 2060 (Figure 4.4).

Secondary plastics use can be boosted in two ways. First, increases in recycling can boost the availability of scrap material for use in secondary plastics production. Second, on the demand side, there is a pull effect from increased demand for plastics as well as increased production costs for primary plastics. The *Baseline* scenario assumes no new policies are introduced to incentivize a shift away from primary plastics, and thus this lever is not very strong. Nonetheless, the share of secondary plastics increases even in the absence of stronger policies, as more scrap becomes available keeping production costs for secondary plastics relatively low so that secondary production can compete better with primary production. The increase is, however, not nearly enough to overcome the strong increase in total plastics demand, leading to a significant increase in primary plastics production.

Figure 4.4. Primary plastics will still make up the lion's share of production in 2060

Primary and secondary plastics production in million tonnes (Mt), *Baseline* scenario, 1950-2060



Note: 2019 (dashed line).
Source: OECD ENV-Linkages model.

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[9] Plastics use and production for 2019 were estimated by calculating the amount of plastics labelled for recycling, minus the plastics lost in the recycling process (during both sorting and conversion). Information on plastics losses was supplied by Leeds University. The evolution of secondary plastics in the *Baseline* scenario was then carefully calibrated to have a match between available plastic waste labelled for recycling (minus losses) and secondary production by region to 2060. See Annex A for details on the methodology and (OECD, 2022[6]) for an overview of base year plastics use.

Due to the increasing use of plastics, biobased plastics production is also projected to increase in the *Baseline* scenario, but at a slower rate than total plastics production, and its share remains marginal (at around 0.5% in 2060).

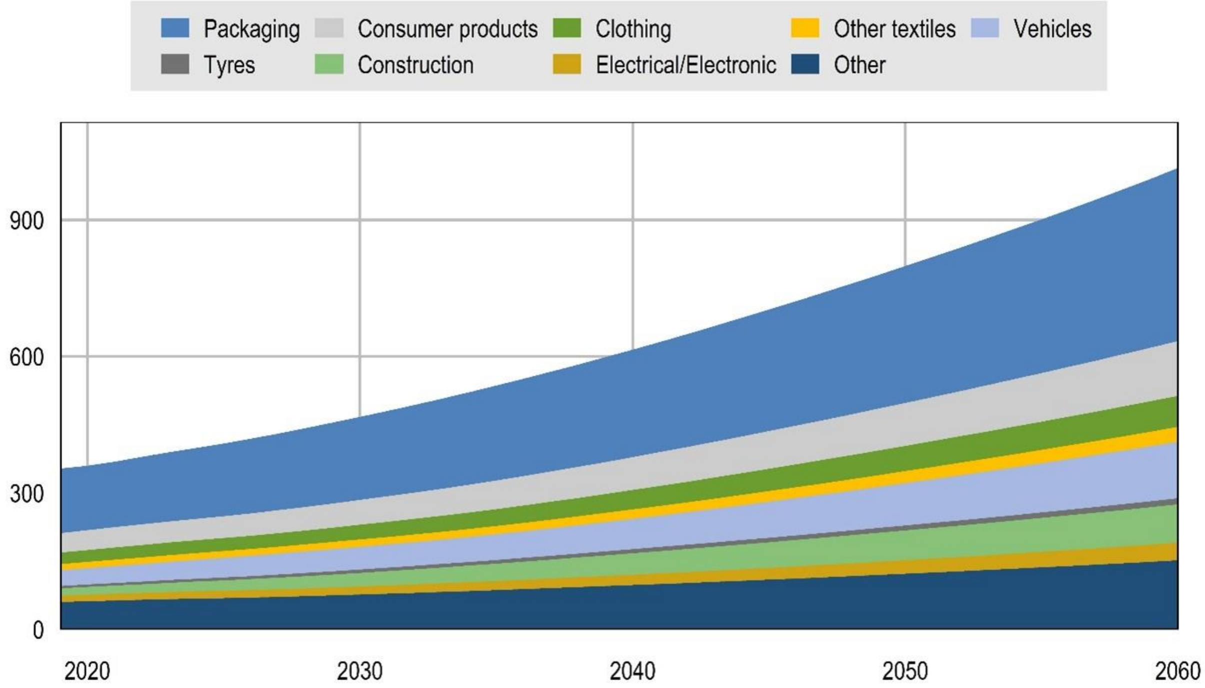
4.2. Projections of plastic waste

The dynamics of plastic waste differ from those of plastics use as there is a time lag between use and waste, the length of which depends on the lifespan of the product (Section 3). For example, on average, plastics used in transport only become waste after 13 years on average, whereas the lifespan of some plastics in construction can be as long as 35 years. Other applications, such as consumer products and packaging, have very short lifespans.

In the *Baseline* scenario, plastic waste is projected to increase substantially in the coming decades, rising from 353 Mt in 2019 to 1 014 Mt in 2060 (Figure 4.5). In this scenario, continued socio-economic developments and economic growth, including recovery from the COVID-19 pandemic, lead to rapidly rising plastics use. An important trend is that emerging and developing economies catch up to higher income countries, implying that plastics use increases faster in these countries.

Figure 4.5. Plastic waste is projected to almost triple by 2060

Plastic waste by application in million tonnes (Mt), *Baseline* scenario



Source: OECD ENV-Linkages model.

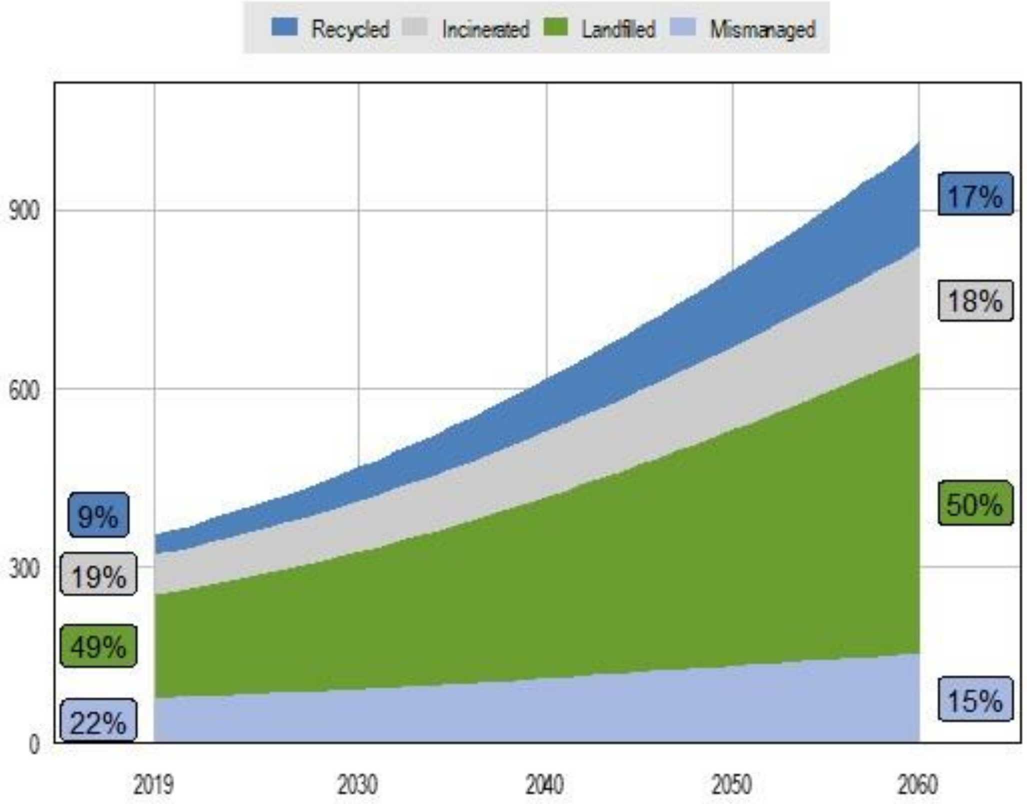
ENV-Linkages also projects the future shares for recycled, incinerated, landfilled and mismanaged waste to 2060 (Figure 4.6). In the *Baseline scenario*, recycling is projected to grow most, increasing from 33 Mt in 2019 to 176 Mt in 2060. Thus, the share of plastic waste that is recycled almost doubles, reaching 17% of all waste generated, from 9% in 2019. This is a key indicator of circularity and shows that over time the global plastic economy becomes more circular

Incineration and landfilling also experience steady growth, with landfilling projected to remain the most common waste management category, although regional shares differ widely depending on how scarce land is in the region.[10] The amount of landfilled plastic waste triples from 174 Mt in 2019 to 507 Mt in 2060 while incinerated waste increases from 67 Mt to 179 Mt. Globally, the share of landfilling remains constant at around 50% while incineration accounts for a little less than 20% of plastic waste in 2060.

Mismanaged waste is projected to grow more slowly than other end-of-life fates. This is because recycling absorbs a bigger share of waste, and emerging countries invest part of their additional income in improved waste management facilities and litter collection. Consequently, the share of mismanaged waste decreases from 22% in 2019 to 15% in 2060. However, the amount of mismanaged waste still increases, driven by the growth in waste – nearly doubling from 79 Mt in 2019 to 153 Mt in 2060.

Figure 4.6. Sanitary landfilling will remain the most widespread waste management approach

Plastic waste by waste management category in million tonnes (Mt), *Baseline* scenario



Note: The numbers to the left and right show the share of each fate in 2019 and 2060 respectively.
Source: OECD ENV-Linkages model.

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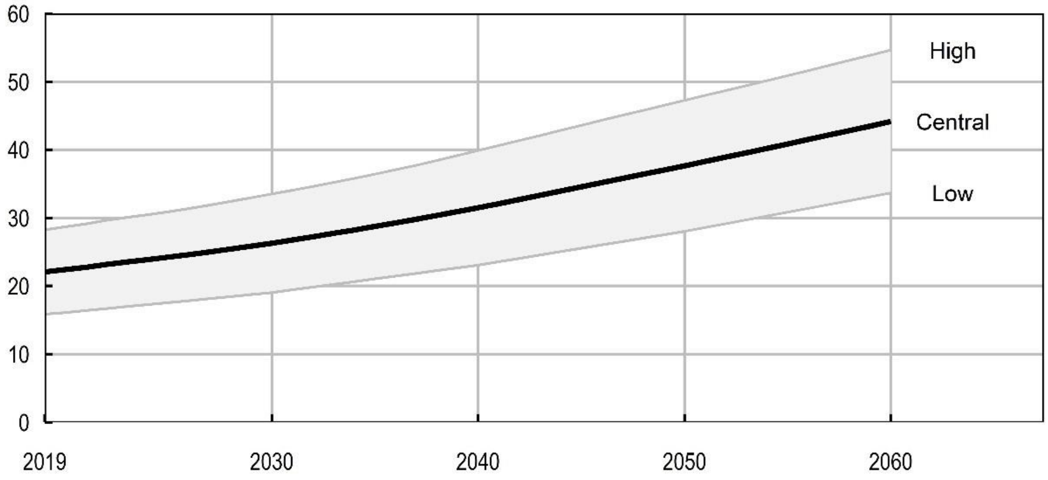
[10] Landfilled waste implies an increased demand for suitable landfilling sites, putting additional pressure on land use. However, by taking the land density into account in the projection of the share of landfilling in the region, the largest increases in area required for landfilling are in regions that have relatively ample space available. However, landfilling often occurs close to city centres, which could still pose problems. Furthermore, the environmental implications of increased land use for waste management could not be taken into account in the analysis.

4.3. Projections of plastic leakage

The global annual plastics leaked to the environment is projected to double, from 22 million tonnes (Mt) in 2019 to 44 Mt in 2060 (Figure 4.7) in the *Baseline* scenario. The lack of robust knowledge surrounding certain critical factors, such as the share of mismanaged waste that is lost to the environment, means these estimates have wide uncertainty ranges depending on the assumptions employed, with the high estimate being almost 55 Mt and the low estimate 34 Mt in 2060 (16 Mt – 28 Mt in 2060). Despite the uncertainty, the projections show that in the *Baseline* scenario, plastic leakage will increase over time and add to the plastic stocks already accumulated in the environment.

Figure 4.7. All estimates agree that global plastic leakage is growing, though magnitudes vary

Plastic leakage to the environment in million tonnes (Mt), *Baseline* scenario

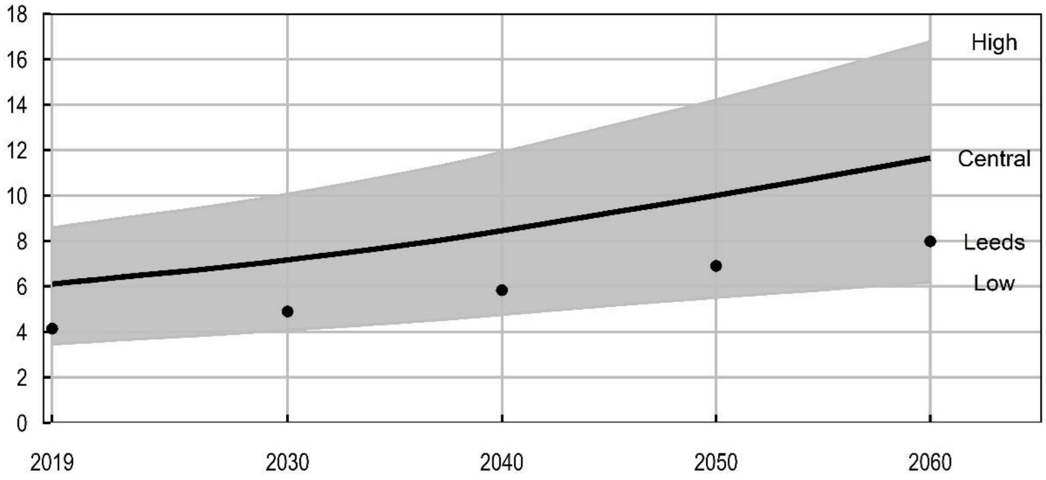


Source: OECD ENV-Linkages model, based on Ryberg et al. (2019[11]) (high estimate) and Cottom et al. (2022[45]) (low estimate).

Annual global plastic leakage into aquatic environments is projected to almost double, from 6.1 Mt in 2019 to 11.6 Mt in 2060 (“Central estimate” in Figure 4.8). The wide range, with a low estimate of 6.2 Mt and a high estimate of 16.8 Mt, emphasises the substantial uncertainty given the lack of empirical data. To further underline the uncertainty, the dots in the represent estimates provided by Leeds University. The numbers from Leeds University are lower than the OECD central estimate but fall within the uncertainty range at the lower end, starting from 4.1 Mt in 2019 to 8 Mt in 2060. Regardless of the size of the estimate, however, the trend indicates that the increasing use of plastics, only partly abated by the slow improvement of global waste management, will steadily drive up the annual amounts of plastics leaked to aquatic environments.

Figure 4.8. Global leakage to aquatic environments could at least double by 2060

Plastic leakage to aquatic environments in million tonnes per year (Mt), *Baseline* scenario

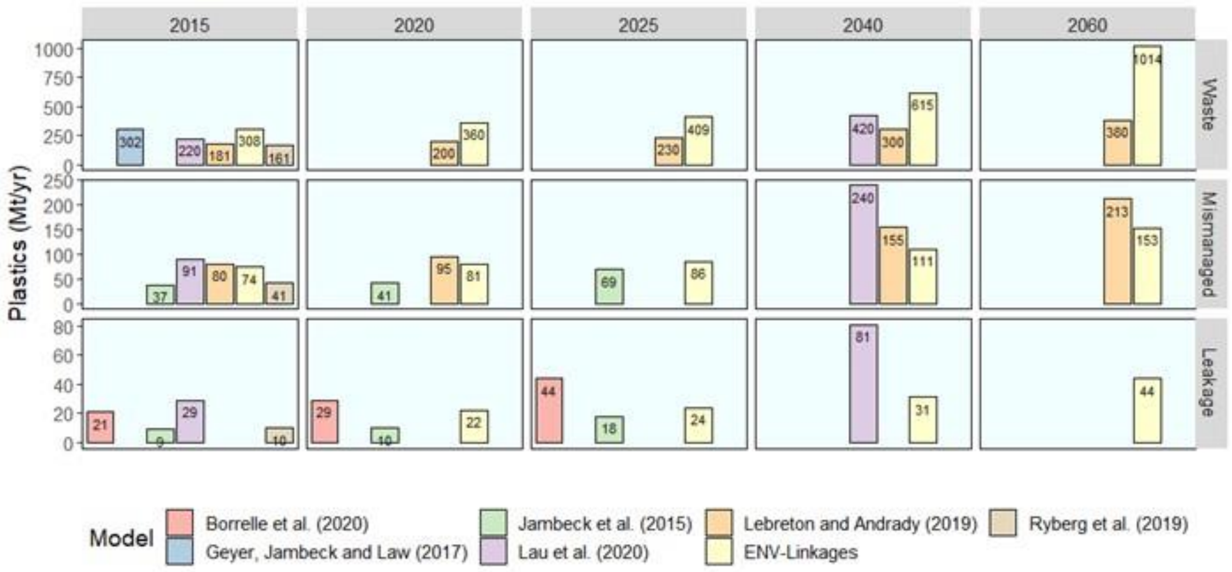


Note: High and low correspond to low and high emission probability ranges. The dots correspond to Leeds University estimates.
Source: OECD ENV-Linkages model, based on Lebreton and Andrady (2019[18]), Lebreton, Egger and Slat (2019[19]) and Cottom et al (2022[45]).

5 Discussion

The projections with ENV-Linkages differ from previous studies due to the differences in methodology and data sources (Figure 5.1), such as the assumed drivers of future economic growth. Some studies use solely socio-economic projections (e.g. changes in population or economic growth). Other models use mainly historical observations as the basis for projections. Meanwhile, ENV-Linkages takes into account structural and technology changes within its CGE-framework. Therefore, it is able to capture a much more complex set of economic variables, such as the servitisation of the economy.

Figure 5.1. There is a diverse set of estimates and projections for quantities of plastics



Note: Values are based on reported results and rounded to the nearest integer. 2015 values reported for Borelle et al. (2020[5]) and for Lau et al. (2020[6]) refer to 2016 values.
Source : Borelle et al. (2020[5]), Jambeck et al. (2015[1]), Lebreton and Andrady (2019[4]), Geyer, Jambeck and Law (2017[2]), Lau et al. (2020[6]), OECD (2022[17]; 2022[18]) for ENV-Linkages, Ryberg et al. (2019[3]).

The approach used to model plastic waste generation can also affect plastic waste estimates. The ENV-Linkages methodology has a wider scope in terms of data coverage on waste as it accounts for all plastic waste (both industrial and municipal solid waste), while other studies, such as Jambeck et al. (2015[1]) and Lau et al. (2020[6]) only consider municipal solid waste. Furthermore, the ENV-Linkages model, in line with Geyer, Jambeck and Law (2017[2]), uses lifetime distributions by applications to estimate plastic waste. Meanwhile, other studies use a bottom-up approach, estimating waste generation from per capita values.

Uncertainties compound over the value chain, and thus a detailed sectoral and polymer-specific approach such as the one used in ENV-Linkages is helpful in ensuring the credible range is fairly small. The farther one goes along the value chain, the more divergent estimates of plastics become. The ENV-Linkages mismanaged plastic waste base year estimates are in the same range as other studies, as it follows Ryberg et al. (2019[3]) and uses World Bank data (2018[9]), while also including open burning, as in Lau et al.

(2020[6]). The ENV-Linkages models also use of the 1-2% total littering rates following the literature as in Jambeck et al. (2015[1]), but expand on that by having litter collection rates that are both time- and region-specific and that depend on income developments. Furthermore, collected litter is re-attributed to the other waste streams. In total, ENV-Linkages' mismanaged waste projections are lower than those by Lebreton and Andrady (2019[7]) and Lau et al. (2020[8]). Following Ryberg et al. (2019[6]), and municipal solid waste trends from Kaza et al. (2018[9]), ENV-Linkages assumes a significantly lower percentage of mismanaged waste in the projections. Furthermore, the ENV-Linkages projections take into consideration the possible impacts of current policies in the coming decades.

Finally, estimates of plastic leakage in the environment show most divergence due to the complexity and variety of leakage pathways. Some studies use globally uniform leakage rates but physical processes can give rise to complex interactions when plastics enter the environment. Therefore, some studies vary leakage rates along other dimensions (e.g. distance from sea, size of plastic waste, polymer characteristics, etc.). The estimates based on ENV-Linkages, in particular, take into account a complex set of pathways, including leakage into rivers and transport from rivers in the ocean. Therefore, leakage to marine environments is much lower than in other studies as it is assumed that much plastics is stuck in aquatic environments before reaching oceans.

Overall, while the ENV-Linkages methodology leads to the qualitative confirmation of existing consensus on the projected growth of plastics use, waste and leakage, the increased granularity and improved methodology provide significant novel insights and more robust quantitative conclusions.

Annex A. Technical specifications

The ENV-Linkages model

ENV-Linkages is a standard computable general equilibrium model, which is used to study the linkages between the economy and the environment. Production in ENV Linkages is assumed to operate under cost minimisation with perfect markets and constant returns-to-scale technology. The production technology is specified as nested Constant Elasticity of Substitution (CES) production functions in a branching hierarchy. This structure is replicated for each output, while the parameterisation of the CES functions may differ across sectors. The model adopts a putty/semi-putty technology specification, where substitution possibilities among factors are assumed to be higher with new vintage capital than with old vintage capital. In the short run this ensures inertia in the economic system, with limited possibilities to substitute away from more expensive inputs, but in the longer run this implies a relatively smooth adjustment of quantities to price changes. Capital accumulation is modelled as in the traditional Solow/Swan neo classical growth model, where economic growth is assumed to stem from the combination of labour, capital accumulation and technological progress.

Household consumption demand is the result of static maximisation behaviour, which is formally implemented as an “Extended Linear Expenditure System”. A representative consumer in each region – who takes prices as given – optimally allocates disposal income among the full set of consumption commodities and savings. Saving is considered as a standard good in the utility function and does not rely on forward looking behaviour by the consumer. The government in each region collects various kinds of taxes in order to finance government expenditures. Assuming fixed public savings (or deficits), the government budget is balanced through the adjustment of the income tax on consumer income. In each period, investment net-of-economic depreciation is equal to the sum of government savings, consumer savings and net capital flows from abroad.

International trade is based on a set of regional bilateral flows. The model adopts the Armington specification, assuming that domestic and imported products are not perfectly substitutable. Moreover, total imports are also imperfectly substitutable between regions of origin. Allocation of trade between partners then responds to relative prices at the equilibrium.

Market goods equilibria imply that, on the one side, the total production of any goods or services is equal to the demand addressed to domestic producers plus exports; and, on the other side, the total demand is allocated between the demands (both final and intermediary) by domestic producers and the import demand.

ENV-Linkages is fully homogeneous in prices and only relative prices matter. All prices are expressed relative to the numéraire of the price system that is arbitrarily chosen as the index of OECD manufacturing exports prices. Each region runs a current account balance, which is fixed in terms of the numéraire.

As ENV-Linkages is recursive-dynamic and does not incorporate forward-looking behaviour, price-induced changes in innovation patterns are not represented in the model. The model does, however, entail technological progress through an annual adjustment of the various productivity parameters, including e.g. autonomous energy efficiency and labour productivity improvements. Furthermore, as production with new capital has a relatively large degree of flexibility in choice of inputs, existing technologies can diffuse to other firms. Thus, within the CGE framework, firms choose the least-cost combination of inputs, given the existing state of technology. The capital vintage structure also ensures that such flexibilities are larger in the long run than in the short run.

Modelling plastics in ENV-Linkages model

ENV-Linkages includes data on plastics use, waste and waste treatment. In ENV-Linkages, plastics projections follow economic projections, and, more precisely, the evolution of the production and consumption of goods in different sectors and regions. The sectoral aggregation of the model adopted in this report is given in Table A.1, while the regional aggregation is presented in Table A.2. The data sources used to model plastics are specified in Table A.3.

Table A.1. Sectoral aggregation of ENV-Linkages

Agriculture, fisheries and forestry	Manufacturing
Paddy rice	Food products
Wheat and meslin	Textiles
Other grains	Wood products
Vegetables and fruits	Chemicals
Oil seeds	Basic pharmaceuticals
Sugar cane and sugar beet	Primary rubber and plastic products
Fibres plant	Secondary plastic products
Other crops	Pulp, paper and publishing products
Cattle and raw milk	Non-metallic minerals
Other animal products	Fabricated metal products
Fisheries	Electronics
Forestry	Electrical equipment
	Motor vehicles
Non-manufacturing Industries	Other transport equipment
Coal extraction	Other machinery and equipment
Crude oil extraction	Other manufacturing including recycling
Natural gas extraction	Iron and steel
Other mining	Non-ferrous metals
Petroleum and coal products	Services
Gas distribution	Land transport
Water collection and distribution	Air transport
Construction	Water transport
Electricity transmission and distribution	Insurance
Electricity generation (8 technologies)	Trade services
Electricity generation: Nuclear electricity; Hydro (and Geothermal); Solar; Wind; Coal-powered electricity; Gas-powered electricity; Oil-powered electricity; Other (combustible renewable, waste, etc.).	Business services n.e.s.
	Real estate activities
	Accommodation and food service activities
	Public administration and defence
	Education
	Human health and social work

Source: Authors' own elaboration.

Table A.2. Regional aggregation of ENV-Linkages

Macro regions		ENV-Linkages countries and regions	Most important comprising countries and territories
OECD	OECD America	USA	United States of America
		Canada	Canada
		Other OECD America	Chile, Colombia, Costa Rica, Mexico
	OECD Europe	OECD EU countries	Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden
		OECD Non-EU countries	Iceland, Israel,[1] Norway, Switzerland, Türkiye, United Kingdom
	OECD Pacific	OECD Oceania	Australia, New Zealand
		OECD Asia	Japan, Korea
Non-OECD	Other America	Latin America	Non-OECD Latin American and Caribbean countries
	Eurasia	Other EU	Bulgaria, Croatia, Cyprus,[2] Malta, Romania
		Other Eurasia	Non-OECD European and Caspian countries, including Russian Federation
	Middle East and Africa	Middle East & North Africa	Algeria, Bahrain, Egypt, Iraq, Islamic Rep. of Iran, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Tunisia, United Arab Emirates, Syrian Arab Rep., Western Sahara, Yemen
		Other Africa	Sub-Saharan Africa
	Other Asia	China	People's Republic of China, Hong Kong (China)
		India	India
		Other non-OECD Asia	Other non-OECD Asian and Pacific countries

Source: Authors' own elaboration.

Table A.3. Data sources and methodologies

Category	Variable	Source
Production	Primary and secondary economic split	OECD ENV-Linkages model, based on GTAP10 (Aguiar et al., 2019[5]) split using Exiobase for cost structure (Stadler et al., 2018[8]), Grand View Research (2020[9]) data for total shares (in tons).
	Plastic sectors	OECD ENV-Linkages model projections, resulting from mapping of sectoral/polymer flows to economic baseline. Secondary plastics incorporates recycling loss rates from the literature (Cottom et al., 2022[10]; Chruszcz and Reeve, 2018[11]; Roosen et al., 2020[12]; VinylPlus, 2019[13]).
Use by region, application and polymer	Historical use	Global consumption from Geyer, Jambeck and Law (2017[14]) for 1950-2014. Regional split based on waste weight estimates from Kaza et al. (2018[15]) The split by polymers and applications per region is based on weight estimates from Ryberg et al. (2019[61]) in 2015, and is constant for 1950-2014.
	Use	For the calibration year (2015), primary plastics use by polymer and application from Ryberg et al. (2019[61]) has been associated to different sectors and regions in the OECD ENV-Linkages model. Secondary plastics use stems from waste generation (derived in the model), recycling rates (see below) and recycling loss rates from the literature (Cottom et al., 2022[10]; Chruszcz and Reeve, 2018[11]; Roosen et al., 2020[12]; VinylPlus, 2019[13]). For future years, OECD ENV-Linkages model projections result from the mapping of sectoral/polymer flows to economic baseline.
Waste by region, application and polymer	Historical waste	OECD ENV-Linkages model, based on historical consumption (for 1950-2015), and product lifespans from Geyer, Jambeck and Law (2017[14]).
	Waste	OECD ENV-Linkages model projections, based on product lifespans from Geyer, Jambeck and Law (2017[14]).
Waste management end-of-life fates	Recycling share	For 1980-2019: Country sources, Geyer, Jambeck and Law (2017[14]), and Kaza et al. (2018[15]). Rates for non-MSW assumed to match MSW.
	Incineration share	For 1980 -2019: Geyer, Jambeck and Law (2017[14]) and Kaza et al. (2018[15]) Rates for non-MSW assumed to match MSW.
	Sanitary landfilling	Cross country regression (residual) based on What a Waste 2.0 (Kaza et al., 2018[15]) (*) Rates for non-MSW assumed to match MSW, when excluding littering.
	Littering share	(Jambeck et al., 2015[17]) for share in MSW and zero for non-MSW.
	Mismanaged share	Cross-country regression based on Kaza et al. (2018[15]) (*) Rates for non-MSW assumed to match MSW, when excluding littering.
Environmental impacts	Total leakage of macroplastics and microplastics to the environment by category	Based on plastic consumption, waste and waste management projections from OECD ENV-Linkages model, adapted from Ryberg et al. (2019[18]) methodology. The central estimate for macroplastic leakage from mismanaged waste (the largest source of leakage) is equal to the average between the estimate provided with the methodology of Ryberg et al. (2019[18]) and the estimate provided by Leeds University (Cottom et al., 2022[10]).
	Plastic leakage and accumulation in aquatic environments	Based on waste management projections from OECD ENV-Linkages model, and the leakage estimates described above, adapted from the Lebreton and Andrady (2019[19]) methodology.
	Plastic leakage to air from terrestrial transport	Based on transport projections from OECD ENV-Linkages model, adapted from Evangeliou et al., (2020[20]) methodology.
	GHG emissions for plastic lifecycle	Based on plastic consumption, waste and waste management projections from OECD ENV-Linkages model, based on Zheng and Suh (2019[21]).

Note: (*) The cross-country regressions based on the What a waste 2.0 database (Kaza et al., 2018[15]) include:
a) $waste\_pc_i = \alpha + \beta * ln(gdp\_pc_i) + r_i$
b) $inc_i/(inc_i + dis_i) = \alpha + \beta * ln(gdp\_pc_i) + r_i$
c) $mis_i/dis_i = \alpha + \beta * ln(gdp\_pc_i) + oecd_i$
where waste_pc = MSW per capita, mis = mismanaged waste, inc = incinerated waste, dis = mismanaged + landfilled, gdp_pc = GDP per capita, oecd = dummy for OECD economies, r = regional dummies for 15 regions of ENV-Linkages, i = country.
Source: Authors' own elaboration.

Additional information on modelling losses

A probability of plastic waste items being selected at the sorting stage based on material, value was applied to each of the packaging and plastic types, as detailed in Table A A.4, Table A.5 and Table A.6. These probabilities were estimated using cost data summarised by SystemiQ and the Pew Charitable Trust (2020[26]), recyclability imperatives detailed by Recoup (2019[27]) and data on material actually recycled reported by Antonopoulos, Faraca and Tonini (2021[28]) and Plastics Recyclers Europe (2020[29]). In general HDPE, PET and LDPE were considered to have a 100% chance of being selected for reprocessing at the MRF and PVC and PS were considered to have 0% chance of being selected for reprocessing at the MRF. Although the evidence for PVC is more clear-cut, Antonopoulos, Faraca and Tonini (2021[28]) reported some post-consumer PS selection taking place in Europe. However these quantities are reported by Plastics Recyclers Europe (2020[29]) to be small and unusual, there is a likelihood that they do not refer to post-consumer material. The probability was set to zero for packaging but an overall probability of 98.5% was set to allow for some small occurrences of non-packaging material.

The loss rates at the reprocessor were approximated using data on plastic content reported by Roosen et al. (2020[30]); non-plastic content reported was excluded and the relative masses normalised.

High-income countries were assumed to have formal collection and the plastic packaging reported there was subject to loss rates at both sorting and reprocessing. Low and middle-income countries were assumed to have informal collection and the loss rates were therefore assumed to occur only at the reprocessing stage as informal actors selectively collect.

The assumptions for non-packaging applications were based largely on estimates from the project expert team, as there are no published data to support them. Consumer and institutional products were assumed to be the same as packaging except for PVC for which evidence from VinylPlus (2019[31]) indicates some recycling takes place. For the textiles (fibres), an estimate of 20% from financial modelling by Thompson et al. (2012[32]) was used in the absence of any other robust data. Readers should note that this loss rate is approximated on the basis that post-consumer textiles that been recycled into shoddy fibres and/or flocking (stuffing) rather than items that have been ‘reused’ and are out of scope of this study.

Table A.4. Assumptions used to determine loss rates for plastic packaging waste that has been collected for recycling

Plastic item[1]	Plastic type by dominant polymer[1]	Weighted composition[1]	High-income countries			Low- & middle-income countries		
			Probability of being rejected before reprocessing[2]	Loss rate at reprocessor adjusted for wastage[3]	Net losses after sorting & reprocessing[4]	Probability of being rejected before reprocessing[2]	Loss rate at reprocessor adjusted for wastage[3]	Net losses after sorting & reprocessing[4]
Film LA recycling sacks	LDPE	2.9	100	0.00	2.90	25	1.00	0.75
FILM Other film	LDPE	11.2	100	0.00	11.20	25	1.00	2.88
FILM Carrier bags	LDPE	1.5	100	0.00	1.50	25	1.00	0.39
B PET NATURAL	PET	26.4	0	13.45	3.55	0	13.45	3.55
B PET JAZZ	PET	3.1	0	13.45	0.42	0	13.45	0.42
B HDPE Milk Bottles	HDPE	13.2	0	15.93	2.10	0	15.93	2.10
B HDPE All non-milk bottles	HDPE	7.7	0	15.93	1.23	0	15.93	1.23
B PVC ALL	PVC	0	100	0.00	0.00	100	0.00	0.00
B PP ALL	PP	0.4	50	21.31	0.24	0	21.31	0.09
Pack PET NATURAL	PET	10.3	0	14.63	1.51	0	14.63	1.51
Pack PET JAZZ	PET	0.5	0	14.63	0.07	0	14.63	0.07
Pack HDPE NATURAL	HDPE	0.1	100	0.00	0.10	0	14.63	0.01
Pack HDPE JAZZ	HDPE	0.6	100	0.00	0.60	0	14.63	0.09
Pack PVC ALL	PVC	0.1	100	0.00	0.10	100	0	0.10
Pack PP NATURAL	PP	4.4	100	0.00	4.40	0	2.08	0.09
Pack PP JAZZ	PP	5.3	100	0.00	5.30	0	2.08	0.11
Pack PS ALL	PS	1.5	100	0.00	1.50	100	0	1.50
Pack EPS ALL	EPS	0.4	100	0.00	0.40	100	0	0.40
Black PET	PET	1.9	100	0.00	1.90	100	0	1.90
Black PP	PP	0.6	100	0.00	0.60	100	0	0.60
Black Other	Mixture	1.1	100	0.00	1.10	100	0	1.10
Other	Mixture	0.2	100	0.00	0.20	100	0	0.20
Unidentified	Mixture	1.9	100	0.00	1.90	100	0	1.90
Plastic non-packaging	Mixture	4.4	100	0.00	4.40	100	0	4.40

1. (Chruszcz and Reeve, 2018[24]).

2. Assumptions based on polymer value SYSTEMIQ & The Pew Charitable Trust (2020[26]), recyclability reported by Recoup (2019[27]), and material reported to have been recycled by Antonopoulos, Faraca and Tonini (2021[28]) and Plastics Recyclers Europe (2020[29]).

3. (Roosen et al., 2020[30]). 4. Calculated.

Table A.5. Average loss rates by plastic type and application for high income countries and low- middle income countries (MSW)

Plastic type by dominant polymer	Consumer & Institutional			Electrical/Electronic			Packaging[1]			Textile sector - clothing			Textile sector - others			Total (t y^{-1})
	Mass (t y^{-1})	Loss rate HIC (%)	Loss rate LMIC (%)	Mass (t y^{-1})	Loss rate HIC (%)	Loss rate LMIC (%)	Mass (t y^{-1})	Loss rate HIC (%)	Loss rate LMIC (%)	Mass (t y^{-1})	Loss rate HIC (%)	Loss rate LMIC (%)	Mass (t y^{-1})	Loss rate HIC (%)	Loss rate LMIC (%)	
Fibres										0.17	20.0[4]	20.0[4]	0.10	20.0[4]	10.0	0.27
HDPE										0.2	20.0[4]	20.0[4]	0.1	20.0[4]	10.0	0.3
LDPE, LLDPE	1.9	18.7	15.9	0.2	95.0	40.0	11.8	18.7[2]	15.9[2]							13.9
Other	1.4	79.0	80.5	0.2	100.0	50.0	6.9	79.0	80.5							8.5
PET	0.0	98.0	98.0	0.0	100.0	50.0	0.0	98.0	98.0							0.1
PP							9.6	17.6	17.6							9.6
PS	2.8	98.5	8.3	0.6	95.0	40.0	6.8	98.5	8.3							10.2
PUR	0.4	100.0	100.0	0.1	100.0	100.0	0.5	100.0	100.0							0.9
PVC	0.2	40.0[3]	10.0[3]	0.1	100.0[3]	100.0[3]	0.0	100.0[3]	100.0[3]							0.2

Source: Cottom et al. (2022[10]).

Table A.6. Average loss rates by plastic type and application for high income countries and low- middle income countries (Non-MSW)

Plastic type by dominant polymer	Building and Construction			Industrial/Machinery			Other			Transportation - Other			Total (t y^{-1})
	Mass (t y^{-1})	Loss rate HIC (%)	Loss rate LMIC (%)	Mass (t y^{-1})	Loss rate HIC (%)	Loss rate LMIC (%)	Mass (t y^{-1})	Loss rate HIC (%)	Loss rate LMIC (%)	Mass (t y^{-1})	Loss rate HIC (%)	Loss rate LMIC (%)	
Fibres							0.1	100.0	100.0	0.0	100.0	100.0	0.1
HDPE	1.0	20.0	5.0	0.1	20.0	5.0	1.1	20.0	5.0	0.6	98.0	90.0	2.9
LDPE, LLDPE	0.1	2.0	2.0	0.1	2.0	2.0	0.7	2.0	2.0	0.1	98.0	90.0	1.0
Other	0.0	100.0	100.0				0.2	100.0	100.0	0.1	100.0	100.0	0.4
PP	0.2	20.0	5.0	0.1	20.0	5.0				1.2	100.0	100.0	1.5
PS	0.1	100.0	100.0				0.1	100.0	100.0				0.2
PUR	0.1	40.0	10.0	0.0	40.0	10.0	0.4	40.0	10.0	0.2	100.0	100.0	0.6
PVC	0.6	18.7[3]	18.7[3]				0.4	18.7[3]	18.7[3]	0.1	100.0[3]	100.0[3]	1.1

1. Calculated from Chruszcz and Reeve (2018[24]) and Roosen et al. (2020[30]).
2. Calculated from Lau et al. (2020[25]).
3. Approximated from data reported by VinylPlus (2019).
4. Thompson Willis and Morley (2012[32]).

Source: Estimated by project team, if not stated in the notes.

For simplicity, the EU regions, the USA, and Canada were considered to have formal collection and all other regions were considered to have predominantly informal collection for recycling. The exception was People's Republic of China (hereafter 'China') which has been undergoing a partial transition from informal to formal collection for recycling. Due to the lack of robust data on the informal recycling sector, this component of the model assumed a 70 : 30 ratio for informal: formal collection for recycling. Table A.7 puts forward the outcome of the technical calculations. The loss rates of PS and other have been lowered to 72.3%, the second highest level of losses between polymers, to represent that these polymers are sometimes recycled, but only in small quantities. Furthermore, to reflect that a large share of recycling of PET is rather a downcycling transformation of PET into fibres, the modelling assumes 35% of recycled PET is transformed into fibres.

Table A.7. Average loss rates by plastic type and OECD region for MSW and non-MSW combined

Region	HDPE	LDPE, LLDPE	Other	PP	PS	PUR	PVC	Fibres	PET	Mean
USA	23.7	71.4	99.8	96.1	100	58.1	47.8	35	17.6	51.8
Canada	23.6	71.5	99.8	96.2	100	58.1	48.3	34.9	17.6	51.9
Other OECD America	16.7	70.8	95.2	18.1	100	30.8	52.9	42.2	17.6	31.3
OECD EU countries	22.6	69.9	99.8	93.8	100	54	38.2	41.7	17.6	49.7
OECD Non-EU countries	22.2	70.9	99.8	95.1	100	54	42.2	41.1	17.6	50.2
OECD Oceania	19.1	76.4	98.7	23.2	100	46.9	53.7	19.1	17.6	33.3
OECD Asia	21.2	72	99.8	94.9	100	51.8	39.9	33.3	17.6	49.6
Latin America	16.6	71.6	95.2	16.7	100	30.1	59.8	41.4	17.6	31.1
Other EU	21.1	74	97.3	30.2	100	51	51.9	35.2	17.6	35.8
Other Eurasia	21.1	74.3	97.2	29.4	100	50.8	56.5	34.4	17.6	35.9
Middle East & North Africa	17.7	73.3	95.9	20.2	100	37.2	52.6	33.2	17.6	32.4
Other Africa	16.5	71.9	95.5	15.9	100	29.3	61.1	44.4	17.6	31
China	18.5	73.9	97	41.4	100	40.7	63.3	31.8	17.6	37.7
India	17.2	76	96.1	16.1	100	35.2	69.2	20.2	17.6	31.9
Other non-OECD Asia	19.2	75	96.6	23.1	100	45.7	67	27.3	17.6	33.7
Mean	**20.3**	**72.3**	**98.1**	**59.8**	**100.0**	**47.2**	**48.9**	**34.1**	**17.6**	**42.1**

Source: Estimated by project team.

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