Technical Appendix

Breaking the Plastic Wave 2025: An Assessment of the Global System and Strategies for Transformative Change

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1. Introduction

This Technical Appendix describes the data sources and assumptions underlying the "Breaking the Plastic Wave 2025" report, hereafter referred to as BPW2. It is organized as follows:

- **Section 2: Pathways model overview** describes the Pathways tool used to model the updated flows of plastic and the associated impacts for BPW2.
- **Section 3: Modelling scope** describes the modelling scope for BPW2 and a detailed comparison of the scopes of the first "Breaking the Plastic Wave" (BPW1) report and BPW2.[1]
- **Section 4: Methods for macroplastic Business as Usual** describes the data, methods and assumptions applied in the development of the Business as Usual (BAU) for macroplastics.
- **Section 5: Methods for macroplastic impacts** describes the data, methods and assumptions used to model macroplastic impacts, including human health impacts, greenhouse gas (GHG) emissions and economic impacts.
- **Section 6: Methods for macroplastic System Transformation** describes the data, methods and assumptions applied in the development of the System Transformation for macroplastics.
- **Section 7: Methods for microplastic analysis** describes the data, methods and assumptions underlying the modelling of microplastics, including the methods for both BAU and System Transformation.
- **Section 8: Estimating externalities** provides a discussion of estimating the externalities from the plastic life cycle.
- **Section 9: Case study on health impacts from chemicals in plastic products** provides more detail on the modelling approach and results of the analysis of use-related impacts from plastic that are discussed briefly in the main report.
- **Section 10: Low-end results for System Transformation** provides the results of the low-end estimates applied in System Transformation.

Complete data for BPW2 is available through Zenodo at 10.5281/zenodo.17527022.

2. Pathways model overview

The Pathways model ("Pathways") is a development of the original Plastics-to-Ocean model developed by The Pew Charitable Trusts and professor Dr. Richard Bailey of the University of Oxford.[2] It is a data-driven coupled ordinary differential equation (ODE) model that calculates the flow of mass through predefined waste systems. The BPW2 modelling update included updates and improvements to Pathways by Bailey, as well as the development of new modelling inputs and analysis by ICF and Pew.

For the BPW2 update, ICF and Pew compiled updated data on plastic inventories, flows and impacts and organized them in an SQL database. The database contains individual tables for each set of relevant information, along with bibliographic information and data pedigree scores to inform uncertainty analysis. ICF wrote code in the R programming language to codify the data and assumptions underlying the BPW2 modelling. The code pulls from the SQL database and produces Microsoft Excel files that serve as input sheets to Pathways. Pathways dictates the specific format of the input sheets and the R code translates the data from the database accordingly. The R code includes notes documenting any changes made to the raw data housed in the database to allow for transparency in our methodological process and reproducibility of our modelling results.

2.A. Overview and choice of approach

An ODE modelling framework was chosen for three reasons. First, we are specifically interested in the flow rates of plastic and other materials through the system, in stocks of mass held in the system, and in making accurate quantitative estimates of changes to these stocks and flows. Second, there are continuous feedbacks in the system that complicate model dynamics, and the relationship of the modelled scenario forcings to the outputs cannot be learned from historical data. Third, the model must respond naturally to the effects of discontinuities in forcing under some of the scenarios used, and to the potential for flow constraints to be met abruptly as the model runs (causing higher-order effects), meaning that statistical models trained on finite sets of empirical data would most likely not be able to account for the infinitely variable range of dynamics we see in the results. Given these conditions and requirements, a mechanistic ODE model is an obvious choice, as its outputs are naturally in the form of flows (derivatives) and stocks (integrals), and data-based instantaneous inputs can be used to drive the model.

The core features of individual models (shown graphically in the "system maps"; see Figure 3-1 and Figure 3-2) include the following:

1. Boxes: these represent both stores and processes within the model.
2. Flows: the flow of material mass to/from boxes.
3. Materials: multiple types of materials to flow through the system, including plastic and non-plastic.
4. Inter-model transport: Pathways can run multiple models simultaneously and transport mass between any of the boxes to simulate imports/exports between systems.
5. Constraints: material flows, the capacity of finite sinks and the flux of mass through any of the boxes can be constrained in several ways (including the facility to arbitrarily transport excess mass to designated locations within each model).

2.B. Masses and flows

As indicated in the system maps, the model simulates the flows of mass between boxes, of which there are three types: 1) "sources," representing the primary production of materials and/or their importation; 2) "pass-through" boxes, which re-route flow to subsequent boxes (maintaining typically small transient mass); and 3) "finite sinks," where mass accumulates over time (with no significant outflow).

As described above, the model is formulated as a set of coupled differential equations, which are solved numerically using software written in Matlab® (ver. 2024a). Numerical integration is performed by the ode15s solver (a variable-step, variable-order solver based on the numerical differentiation formulas of orders 1 to 5), which provides solutions for instantaneous mass in each box, reporting at prescribed temporal resolution, from which the rates of flow can be calculated. Conservation of mass within the system is tracked as a measure of numerical accuracy, and the deviation is $<10^{-4}$ % in all cases and typically $<10^{-8}$ %.[3]

Each box has some combination of input and output flow(s), and its change of mass is the difference between these summed inputs and outputs.

$$\frac{dM_i}{dt} = \sum F_{in}(t) - \sum F_{out}(t) \qquad \text{Eq. (1)}$$

where *M* is instantaneous mass (metric tons) in box *i*, *t* is time in years, and *F* is the flow rate (metric tons/yr). The summations are not explicit here and apply to all relevant in/out flows. Note that each *F* is a function of time and that several different formulations are used for both the macro- and microplastic models, as outlined below.

First, the n^{th} flow from box *j* can be defined as a proportion of the available mass in box *j*:

$$F_{j,n}(t) = M_j(t).R.P_{j,n}(t) \qquad \text{Eq. (2a)}$$

where $P_{j,n} \in [0,1]$ is the proportion of the total flow from box *j*. $P_{j,n}(t)$ can be defined as a continuous function ($P_{j,n}(t) = f(t)$), or as an arbitrary timeseries which is interpolated at *t* as required. R is an arbitrary large positive scaling constant that affects the rate at which material is "processed" through the box. This value does not change the resultant equilibrium flow, only the rate at which equilibrium is achieved and so represents the "responsiveness" of the system to changes in driving conditions. A relatively high value of *R* ensures the system reaches equilibrium with the driving conditions relatively quickly (here < 0.1 year) and that transient (instantaneous) masses are relatively low in all but the "sink" boxes (i.e., those with no outflows). A value of 300 was used in all simulations.

Second, in the case where there are *N* flows from box *j*, a flow can be defined as a "plug" flow, a residual to the other *N*-1 flows. Hence, in relation to the proportional flows described above,

$$F_{j,n}(t) = M_j(t).R.\left(1 - \sum_{\forall x \neq n} F_{j,x}(t)\right)\beta_{j,n} \qquad \text{Eq. (2b)}$$

In cases where multiple residual (plug) flows exist, the proportion attributed to each is controlled by $\beta_{j,n} \in [0,1]$, so preferential flow to multiple targets can be achieved (with $\sum_r B_{j,r} = 1$, where *r* indexes the residual flows).

Third, flows can be defined in absolute terms:

$$F_{j,n}(t) = min\left(M_j(t).R,\ K_{j,n}(t)\right) \qquad \text{Eq. (2c)}$$

where $K_{j,n}(t)$ is either a separate continuous function ($K_{j,n}(t) = f(t)$), or an arbitrary timeseries which is interpolated at *t* as required, giving absolute flows precedence over other flow types. The $min(\cdot)$ is included so a prescribed absolute flow cannot exceed the mass available in the (source) box.

Residual flows can also be used when other flows are defined in absolute terms:

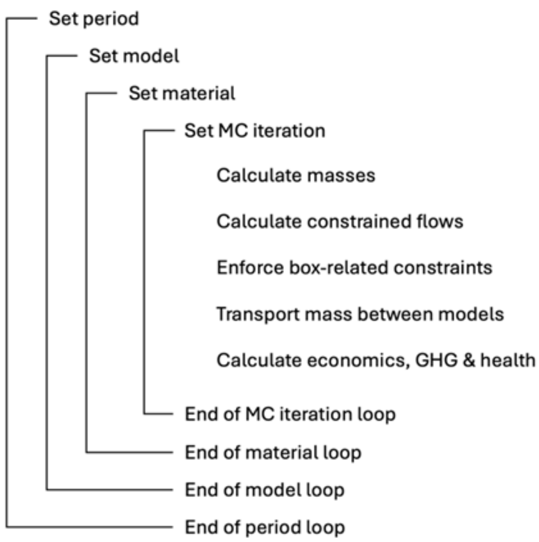
$$F_{j,n}(t) = \left(M_j(t).R - \sum_{\forall x \neq n} F_{j,x}(t)\right)\beta_{j,n} \qquad \text{Eq. (2d)}$$

Mixtures of all of these flow types can be used for any box, and this is handled by the software.

2.C. Time

The simulation typically runs over multiple years and each year is divided in to n_p equal time periods ($n_p = 20$ in the current set of simulations; the time-resolution of calculations within each period is approximately 4 hours). Over the time period, each model (each one of the connected system maps) updates masses and flows of all material types. At the end of the period, constraints which apply to the activities of the boxes (the total mass held in the box and/or the material mass flowing through the box) are applied, and transport of mass between models is updated. The calculation schedule is outlined in Figure 2-1. Note this schedule also includes a Monte Carlo (MC) iteration, which is described below.

Figure 2-1. The Calculation Schedule for Pathways



2.D. Constraints

Various constraints can be applied in the model. They control both flows and stored masses within the system, all of which can be applied over specified time windows. Broadly, there are two types of constraints: (i) constraints on individual flows (which are applied during the flow calculations) and (ii) constraints on the behaviour of boxes, which are applied at the end of each calculation period.

2.D.1. Individual flow constraints

(i) Constant absolute maximum

A maximum absolute flow rate (f_{max}) can be specified (metric tons/year) and the constrained flow ($f_{constrained}$) is calculated as

$$f_{constrained} = \min\left(f_{max}, f\right)$$

where f is the raw calculated flow prior to any constraints being imposed.

(ii) The maximum allowed flow can also be set to increase each year at a compounding growth rate c_f starting from a specified year t_{start} compared to the baseline flow rate $f_{baseline}$,

$$f_{constrained} = \min\left(f, f_{baseline} \cdot \left(1 + c_f\right)^{t-1}\right), \qquad t \geq t_{start}$$

(iii) Maximum relative to another flow

A reference flow (any other flow within the system) can be specified as a reference flow and a constraint imposed that the flow cannot exceed some proportion p_{ref} of the reference flow f_{ref}, starting in year t_start

$$f_{constrained} = \min\left(f, c_{ref} f_{ref}\right), \qquad t \geq t_{start}$$

If constraint conditions are met, the flow is scaled down to the constraint value and mass naturally accumulates in the box. This means other flows can potentially increase (as their source mass grows), so long as their constraints are not triggered. In the case where more mass is arriving in the box than is leaving, the mass in the box naturally grows, which has the potential to trigger a mass-related constraint as described below.

2.D.2. Box constraints

a) Model spin-up phase

Before the main model run there is a "spin-up" phase, which is used to run the model to an equilibrium state under constant year-one conditions. This serves the dual purpose of providing appropriate initial conditions and baseline conditions for calculation of constraints. Some of the flow and mass capacity constraints are not known (in absolute terms) a priori but are required in order to model necessary constraints under future scenarios. To solve this problem, the simulation is run to equilibrium without constraints under the baseline conditions of the first year (including any between-model transport of materials). Flows and masses are then used as baseline values from which subsequent constraints can be calculated and to provide initial conditions for the simulation.

b) Mass constraints

Constraints on the amount of mass held in any box are necessary in some cases, and these are defined in relation to G_j, the baseline mass observed in the equilibrium model run; c, the fractional capacity growth rate; and z, a multiplying factor to account for the relative initial capacity (as compared to the equilibrium mass; for example, a box thought to be operating at 10% above the minimal required capacity would have $z = 1.1$, under the condition $z \geq 0$).

In cases where the box is a finite sink (e.g., landfill), growth in capacity ($c > 0$) is linear, with capacity (g) defined at year t by

$$g_j(t) = G_j z_j + G_j(1 + \mathrm{c_j})(t - 1) \qquad \text{Eq. (3a)}$$

Note that in the case of a sink with no growth in capacity (c=0), capacity simply grows in multiples of the model year number.

If the box is not a finite sink then the capacity at year t is defined

$$g_j(t) = \begin{cases} G_j z_j, & t = 1 \\ G_j z_j (1 + c_j)^{t-1}, & t > 1 \end{cases} \qquad \text{Eq. (3b)}$$

The mass held in each box is compared to its mass constraint at the end of each period, and any mass in excess of the constrained limit is directed to a specified "overflow" box and is added to its mass. The overflow box can be any specified box within the model, including a box whose mass is transported to another model at the end of each period.

2.E. Uncertainty

All model inputs are associated with uncertainty, and this uncertainty is propagated through to the model output using a statistical re-sampling of the inputs over an ensemble simulation (the MC simulation). The width of the uncertainty on each input variable is defined by a data pedigree, and the resultant variation in plastic flows and masses is propagated naturally throughout the MC simulations. Uncertainties related to costs are computed using an additional MC step using parameter uncertainties assigned using the same pedigree system. A total of 200 MC simulations were carried out for plastic flows and costs.

Due to the variability of data availability, quality and uncertainty characterization throughout the plastic system and across geographic archetypes and plastic types, uncertainty on all input variables was standardized across all data using a data pedigree scoring framework. For each input variable calculated, all data sources used were scored across a four attributes matrix (Table 2-1). The scores for each row of the matrix were then summed to yield a total pedigree score.

Pedigree scores for each data source were placed into pedigree categories, with each category assigned an uncertainty (Table 2-2). Uncertainty values represent the upper and lower boundaries of a uniform distribution centred on a single value. For each variable, uncertainty was assigned according to the lowest-quality data source used in the calculation of a mean value.

The highest-quality bin of data was assigned an uncertainty level of ±10%. By default, expert opinions and expert consensus were assigned to data pedigree level 4 – the highest level of uncertainty. The pedigree assignment for each flow can be found in the input sheets.

Table 2-1. Data Pedigree Scoring Matrix

Score	1		2	3	4
Sample size	Representative		Representative under certain conditions and/or in some scenarios	Limited representation: only representative under a specific condition or in one scenario	Unknown
Uncertainty	Uncertainty is measured and reported (e.g., standard deviation, confidence interval,		Uncertainty is not measured nor reported, but all assumptions are stated and the impacts of assumptions on	Assumptions are stated, but no reference is made to the impact of assumptions on results	Uncertainty and assumptions are neither measured nor discussed

Score	1		2	3	4
	interquartile range, mean, error bars)		results are discussed		
Accuracy and reliability	Verified based on empirical measurements and/or direct-to-source interviews		Verified data based on empirical measurements and or direct-to-source interviews with some assumptions and/or estimates to fill data gaps	Non-verified data based on estimates and/or assumptions including qualified estimates (e.g., expert opinion)	Non-verified and/or non-qualified data
Date of publication	< 5 years ago		< 10 years ago	< 15 years ago	> 15 years ago and/or unknown

Table 2-2. Data Pedigree Levels and Uncertainty Ranges

Data pedigree level	Data pedigree score range	Uncertainty range
1	1 to 5	±10%
2	6 to 8	±20%
3	9 to 12	±35%
4	13 to 16	±50%

2.F. Sensitivity analysis

One-at-a-time sensitivity analysis was performed to assess the dependence of each flow of the macro-plastic model on each of the other flows in the model (and their associated economic outcomes). The flow being varied is termed the "driving flow" and the flows being observed the "resultant flows." Calculations were performed under the BAU scenario, for year 1 of the modelled period, to ignore time-dependence in the results. To measure the sensitivity of the resultant flows to the driving flows, driving flows were scaled, one at a time, by 0.95, 1, 1.05, in three successive model runs. The gradient of x=drivingFlow versus y=resultantFlow then defines the sensitivity (in fractional terms). This logic can be extended to composite target flows, such as the dependence of the total flow to aquatic systems on any given individual flow. This analysis allows calculation of, for example, the required change in any flow within the system in order to reduce total plastic pollution flow by some arbitrary amount. As economic, health and GHG emissions are also calculated within the model, this analysis can be extended further to calculate the sensitivity of such features to changes in any individual flow. Calculations for microplastic sensitivities are simpler to calculate because the microplastic systems are linear (i.e., no feedbacks in the system maps), so changes in, for example, total flow to the aquatic environment can be calculated directly from the total system inputs and the flow proportions. No economic analysis (or therefore economic sensitivity analysis) is included in the microplastic modelling.

3. Modelling scope

3.A. Spatial and temporal scope

The modelling period is 2021–2040, with annual results typically presented for years 2025 and 2040. Following the approach taken in BPW1, BPW2 aggregates country-level plastic data to eight geographic archetypes based on income and population density:

- High-income – urban (HI-U).
- High-income – rural (HI-R).
- Upper-middle income – urban (UMI-U).
- Upper-middle income – rural (UMI-R).
- Lower-middle income – urban (LMI-U).
- Lower-middle income – rural (LMI-R).
- Low-income – urban (LI-U).
- Low-income – rural (LI-R).

We apply the World Bank's classification of countries into one of four income groups (low, lower-middle, upper-middle and high), for fiscal year (FY) 2024.[4] The classification is based on gross national income (GNI) per capita for FY 2024 (Table 3-1).

Table 3-1. World Bank Income Group Definitions for FY 2024

World Bank income group	GNI per capita (US$)
Low	<= $1,135
Lower-middle	$1,136–$4,465
Upper-middle	$4,466–$13,845
High	> $13,845

Source: World Bank, World Bank Country and Lending Groups, 2024

To account for the effects of population density, we rely on classifications in the University of Leeds' Spatio-temporal quantification of Plastic pollution Origins and Transportation (SPOT) model and urbanization estimates from the United Nations World Urbanization Prospects data set.[5] The SPOT model categorizes municipal areas as urban, suburban or rural using data from the Global Human Settlement Population. For the BPW2 analysis, we grouped both the urban and suburban classifications under a single "urban" category, while retaining the "rural" classification as is. We then used the U.N. data set to estimate the urban and rural populations within each archetype.

3.B. Scope of materials modelled

BPW2 includes three categories of materials: (1) macroplastics, (2) macroplastic substitutes, and (3) microplastics.

3.B.1. Macroplastic scope

BPW2 models macroplastics from 10 economic sectors: agriculture, aquaculture, building and construction, consumer and institutional products, electrical and electronics, fisheries, industrial and machinery, packaging, textiles and transportation. Table 3-2 provides the key data sources used to model macroplastic flows from each sector, as well as the definition of each macroplastic sector based on information provided by the respective source(s).

Macroplastics from the packaging sector is disaggregated by format (rigid and flexible), product (rigid food, rigid non-food, polyethylene terephthalate [PET]) bottles, other bottles, flexibles and multilayer) and the following seven polymer categories:

- High-density polyethylene (HDPE)
- Low-density polyethylene (LDPE)/linear low-density polyethylene (LLDPE)
- PET
- Polypropylene (PP)
- Polystyrene (PS)/expanded polystyrene (EPS)
- Polyvinyl chloride (PVC)
- Other

Macroplastics from the consumer and institutional products sector is disaggregated by polymer, but not by product type, due to lack of data. Due to data limitations, macroplastics from all remaining sectors is modelled as individual plastic types and is not further disaggregated by polymer or product type.

Table 3-3 presents the complete list of the 52 macroplastic types modelled in BPW2 along with their assigned sector, polymer (where applicable), product (where applicable) and format.

Table 3-2. Macroplastic Sector Definitions and Key Sources

Sector	Definition/scope	Key data sources
Agriculture	Short-term agricultural plastic with lifespans of less than six months, including plastic mulching film, fertiliser containers, coated fertilisers, irrigation drip tapes and plant pods. Long-term agricultural plastic with a lifespan longer than six months, including pond liners, irrigation tubes and greenhouse films.	• Jane Gilbert, Marco Ricci, and Richard H. Thompson, *Assessment of Agricultural Plastics and Their Sustainability: A Call for Action*, 2021, Figures 2 and 10. • B. Le Moine and X. Ferry, *Plasticulture: Economy of Resources*, 2019. • Food and Agriculture Organization of the United Nations, *FAOSTAT: Crops and Livestock Products*, 2023. • Systemiq, *Towards Ending Plastic Pollution by 2040: Technical Annex*, 2023.
Aquaculture	Plastic mesh, feeding pipes, walkways, fishing nets, buoys/floaters and ropes.	• Food and Agriculture Organization of the United Nations, *FishStatJ: Global Capture Production 1950-2022*, March 2025. • Systemiq, *Towards Ending Plastic Pollution by 2040: Technical Annex*, 2023. • Food and Agriculture Organization of the United Nations, *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*, 2024, Table 14.
Building and construction	Pipe, conduit and fittings (including drainage, irrigation, plumbing fixtures and septic tanks), siding, flooring, insulation materials, panels, doors, windows, skylights, bathroom units, gratings and railings.	• Organisation for Economic Co-operation and Development, *Global Plastics Outlook: Policy Scenarios to 2060*, 2022.
Consumer and institutional products	Disposable food service ware (including disposable cups), dinner and kitchenware, toys and sporting goods, household and institutional refuse bags and film, health care and medical products, hobby and graphic arts supplies (including photographic equipment and supplies), apparel, footwear, luggage, buttons, lawn and garden tools, signs and displays and credit cards.	• Organisation for Economic Co-operation and Development, *Global Plastics Outlook: Policy Scenarios to 2060*, 2022. • Dominic Charles and Laurent Kimman, *Plastic Waste Makers Index 2023*, 2023.
Electrical and electronics	Home and industrial appliances (including electrical industrial equipment), wire and cable coverings, communications equipment, resistors, magnetic tape, records and batteries.	• Organisation for Economic Co-operation and Development, *Global Plastics Outlook: Policy Scenarios to 2060*, 2022.

Fisheries	Fishing nets, lines, buoys/floaters and ropes.	• Systemiq, *Towards Ending Plastic Pollution by 2040: Technical Annex*, 2023. • Food and Agriculture Organization of the United Nations, *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*, 2024, Table 14. • Food and Agriculture Organization of the United Nations, *FishStatJ: Global Capture Production 1950-2022*, March 2025.
Industrial and machinery	Engine and turbine parts, farm and garden machinery, construction and related equipment, fishing and marine supplies, machine tools, ordnance and firearms and chemical process equipment.	• Organisation for Economic Co-operation and Development, *Global Plastics Outlook: Policy Scenarios to 2060*, 2022.
Packaging	Includes all plastic packaging, both flexible and rigid, such as bottles, bags, boxes, containers, films and wrappers.	• Organisation for Economic Co-operation and Development, *Global Plastics Outlook: Policy Scenarios to 2060*, 2022. • Dominic Charles and Laurent Kimman, *Plastic Waste Makers Index 2023*, 2023.
Textiles	Includes plastic used in both apparel and non-apparel textiles.	• Textile Exchange, *Materials Market Report 2024*, 2024. • Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020.
Transportation	Includes “tyres” category for all plastic related to tyres, as well as an “other” category for all other transportation-related plastic, such as those in vehicles, railroad equipment, travel trailers, campers, golf carts, snowmobiles, aircraft, military vehicles, ships, boats and recreational vehicles.	• Organisation for Economic Co-operation and Development, *Global Plastics Outlook: Policy Scenarios to 2060*, 2022.

Table 3-3. Macroplastic Plastic Types Modelled in BPW2

Plastic type #	Sector	Polymer	Product	Format
1	Building & construction	x	x	Rigid
2	Consumer & institutional products	Other	x	Rigid
3	Consumer & institutional products	HDPE	x	Rigid
4	Consumer & institutional products	PP	x	Rigid
5	Consumer & institutional products	PS/EPS	x	Rigid
6	Consumer & institutional products	PVC	x	Rigid
7	Consumer & institutional products	LDPE/LLDPE	x	Flexible
8	Consumer & institutional products	PP	x	Flexible
9	Consumer & institutional products	PVC	x	Flexible
10	Electrical/electronics	x	x	Rigid
11	Industrial/machinery	x	x	Rigid
12	Packaging	Other	Rigid non-food packaging	Rigid
13	Packaging	Other	Rigid food packaging	Rigid
14	Packaging	LDPE/LLDPE	Rigid non-food packaging	Rigid
15	Packaging	LDPE/LLDPE	Rigid food packaging	Rigid
16	Packaging	LDPE/LLDPE	Other bottles	Rigid
17	Packaging	HDPE	Rigid non-food packaging	Rigid
18	Packaging	HDPE	Rigid food packaging	Rigid
19	Packaging	HDPE	Other bottles	Rigid
20	Packaging	HDPE	PET bottles	Rigid
21	Packaging	PP	Rigid non-food packaging	Rigid
22	Packaging	PP	Rigid food packaging	Rigid
23	Packaging	PP	Other bottles	Rigid
24	Packaging	PP	PET bottles	Rigid
25	Packaging	PS/EPS	Rigid non-food packaging	Rigid
26	Packaging	PS/EPS	Rigid food packaging	Rigid
27	Packaging	PVC	Rigid non-food packaging	Rigid
28	Packaging	PVC	Rigid food packaging	Rigid
29	Packaging	PVC	Other bottles	Rigid
30	Packaging	PET	Other bottles	Rigid
31	Packaging	PET	Rigid food packaging	Rigid
32	Packaging	PET	Rigid non-food packaging	Rigid
33	Packaging	PET	PET bottles	Rigid
34	Packaging	Other	Flexible packaging	Flexible
35	Packaging	Other	Multilayer packaging	Flexible
36	Packaging	LDPE/LLDPE	Flexible packaging	Flexible
37	Packaging	LDPE/LLDPE	Multilayer packaging	Flexible
38	Packaging	HDPE	Flexible packaging	Flexible
39	Packaging	PP	Flexible packaging	Flexible

Plastic type #	Sector	Polymer	Product	Format
40	Packaging	PP	Multilayer packaging	Flexible
41	Packaging	PS/EPS	Flexible packaging	Flexible
42	Packaging	PVC	Flexible packaging	Flexible
43	Packaging	PVC	Multilayer packaging	Flexible
44	Packaging	PET	Flexible packaging	Flexible
45	Packaging	PET	Multilayer packaging	Flexible
46	Transportation	x	Other	Rigid
47	Textile sector	x	x	Flexible
48	Transportation	x	Tyres	Rigid
49	Agriculture	x	Short term	Flexible
50	Agriculture	x	Long term	Flexible
51	Aquaculture	x	x	Rigid
52	Fisheries	x	x	Flexible

3.B.2. Macroplastic substitutes

To model impacts associated with substitution and reuse policies, BPW2 includes four substitute materials (glass, metal, paper and compostables) and six reuse materials (reusable plastic, glass and metal for return-based reuse and, separately, for refill-based reuse). Table 3-4 provides the key data sources used to model macroplastic substitute flows, as well as the definition of each substitute based on information provided by the respective source(s). Table 3-5 provides the complete list of the substitute material types modelled in BPW2. Note that the material type number starts at 53, following the final number of the plastic types shown in Table 3-3.

Table 3-4. Macroplastic Substitute Definitions and Key Sources

Substitute	Definition/scope	Key data sources
Glass	All glass in residential, commercial and institutional waste. Does not include industrial, medical, hazardous, electronic and construction and demolition glass waste.	• Silpa Kaza et al., *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, 2018 (waste generation flows). • Joshua W. Cottom, Ed Cook, and Costas A. Velis, *A Local-to-Global Emissions Inventory of Macroplastic Pollution*, 2024 (waste collection and sorting flows and managed disposal flows). • Ed Cook, research fellow, University of Leeds, email to The Pew Charitable Trusts, March 18, 2024 (recycling flows).
Metal	All metal in residential, commercial and institutional waste. Does not include industrial, medical, hazardous, electronic and construction and demolition glass waste.	• Silpa Kaza et al., *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, 2018 (waste generation flows).

Substitute	Definition/scope	Key data sources
		• Joshua W. Cottom, Ed Cook, and Costas A. Velis, *A Local-to-Global Emissions Inventory of Macroplastic Pollution*, 2024 (waste collection and sorting flows and managed disposal flows). • Ed Cook, research fellow, University of Leeds, email to The Pew Charitable Trusts, March 18, 2024 (recycling flows).
Paper	All paper in residential, commercial and institutional waste. Does not include industrial, medical, hazardous, electronic and construction and demolition glass waste. Includes paper and cardboard.	• Silpa Kaza et al., *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, 2018 (waste generation flows). • Joshua W. Cottom, Ed Cook, and Costas A. Velis, *A Local-to-Global Emissions Inventory of Macroplastic Pollution*, 2024 (waste collection and sorting flows and managed disposal flows). • Ed Cook, research fellow, University of Leeds, email to The Pew Charitable Trusts, March 18, 2024 (recycling flows).
Compostables	All compostables in residential, commercial and institutional waste. Does not include industrial, medical, hazardous, electronic and construction and demolition glass waste. Classified as the “other” waste category in “What a Waste 2.0.”	• Silpa Kaza et al., *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, 2018 (waste generation flows). • Joshua W. Cottom, Ed Cook, and Costas A. Velis, *A Local-to-Global Emissions Inventory of Macroplastic Pollution*, 2024 (waste collection and sorting flows and managed disposal flows). • Ed Cook, research fellow, University of Leeds, email to The Pew Charitable Trusts, March 18, 2024 (recycling flows).

Table 3-5. Macroplastic Substitutes Modelled

Material type #	Applicable lever	Material
53	Substitute	Glass
54	Substitute	Metal
55	Substitute	Paper
56	Substitute	Compostables
57	Return-based reuse	Plastic
58	Return-based reuse	Metal

Material type #	Applicable lever	Material
59	Return-based reuse	Glass
60	Refill-based reuse	Plastic
61	Refill-based reuse	Metal
62	Refill-based reuse	Glass

3.B.3. Microplastics

Microplastics are defined as pieces of plastic measuring less than 5 mm in size. BPW2 models microplastics from seven key sectors, listed in Table 3-6. Due to data limitations, microplastics in all sectors are modelled as individual plastic types and are not disaggregated by polymer.

Table 3-6. Microplastic Definitions and Key Sources

Sector	Definition/scope	Key data sources
Tyres	Includes tyre wear particles generated from the friction between tyres and the road surface. Includes particles from five tyre types: passenger vehicles, motorbikes, light-duty vehicles, heavy-duty vehicles and airplanes.	• United States Department of Transportation Federal Highway Administration, *Traffic Volume Trends*, 2013. • International Council on Clean Transportation, *European Vehicle Market Statistics Pocketbook 2018/19*, 2019. • Simon Hann et al., *Investigating Options for Reducing Releases in the Aquatic Environment of Microplastics Emitted by (but Not Intentionally Added in) Products: Final Report*, 2018. • Seth Monteith et al., *Carbon Transparency Initiative: Methodology for the Power and Transport Sectors*, 2015. • Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020, 369. • World Bank, *Air Transport, Registered Carrier Departures Worldwide*, 2021.
Recycling	Includes microplastics generated from washing plastic at recycling facilities. Does not include additional microplastics	• Go Suzuki et al., *Mechanical Recycling of Plastic Waste as a Point*

Sector	Definition/scope	Key data sources
	generated during subsequent processing of plastic during recycling (e.g., chopping and grinding processes).	*Source of Microplastic Pollution*, 2022. • Go Suzuki et al., *Global Discharge of Microplastics From Mechanical Recycling of Plastic Waste*, 2024. • Macroplastic modelling. • Quantis and EA – Earth Action, *The Plastic Leak Project Guidelines*, 2020., 2020. • Erina Brown et al., *The Potential for a Plastic Recycling Facility to Release Microplastic Pollution and Possible Filtration Remediation Effectiveness*, 2023. • Johann B. Kasper et al., *Losses and Emissions in Polypropylene Recycling From Household Packaging Waste*, 2025. • Emine Büşra Çolakoğlu and İbrahim Uyanık, *Plastic Waste Management in Recycling Facilities: Intentionally Generated MPs as an Emerging Contaminant*, 2024. • Minh Le Tran et al., *Potential Contamination of Microplastic From Plastic Recycling Enterprises in Ho Chi Minh City, Vietnam*, 2023.
Pellets	Includes pellets that are mishandled during sea transport and at recycling and production facilities, resulting in spills and losses. Does not include pellets lost during land transport.	• Simon Hann et al., *Investigating Options for Reducing Releases in the Aquatic Environment of Microplastics Emitted by (but Not Intentionally Added in) Products: Final Report*, 2018. • Macroplastic modelling. • Quantis and EA – Earth Action, *The Plastic Leak*

Sector	Definition/scope	Key data sources
		Project Guidelines, 2020.
Textiles	Includes microplastics generated from washing synthetic textiles at production facilities and in homes and handwashing textiles outdoors. Does not include airborne emissions. Microplastics generated during washing by consumers only includes synthetic apparel.	• Macroplastic modelling. • Quantis and EA – Earth Action, *The Plastic Leak Project Guidelines*, 2020. Textile Exchange, *Materials Market Report 2024*, 2024. • Textile Exchange, *Materials Production Dashboard*, 2025. • Julien Boucher and Damien Friot, *Primary Microplastics in the Oceans: A Global Evaluation of Sources*, 2017. • Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020. World Trade Organization, *World Trade Statistical Review 2023*, 2023.
Personal care products	Includes plastic microbeads and particles, like glitter, used in personal care and cosmetic products. Includes microplastics entering waste streams from both wash-off and leave-on products. Does not include losses during manufacturing.	• Simon Hann et al., *Investigating Options for Reducing Releases in the Aquatic Environment of Microplastics Emitted by (but Not Intentionally Added in) Products: Final Report*, 2018. • Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020. • Morten W. Ryberg, Alexis Laurent, and Michael Hauschild, *Mapping of Global Plastics Value Chain and Plastics Losses to the Environment: With a Particular Focus on Marine Environment*, 2018. • Alexandra Scudo et al., *Intentionally Added Microplastics in Products: Final Report of*

Sector	Definition/scope	Key data sources
		the Study on Behalf of the European Commission, 2017. • Quantis and EA – Earth Action, *The Plastic Leak Project Guidelines*, 2020.
Paint	Includes microplastics generated from paint losses during application (e.g., through overspray), wear and tear (e.g., through abrasion) and removal. Includes losses from six types of paints: architectural, automotive, general industrial, industrial wood, marine coatings and road markings.	• Paola Paruta, Margherita Pucino, and Julien Boucher, *Plastic Paints the Environment*, 2021.
Agriculture	Includes microplastics introduced to agricultural lands through the application of compost, which can contain plastic particles. We also model secondary microplastics generated when agricultural plastic breaks down over time on agricultural lands. Does not include the breakdown of long-term agricultural plastic, such as greenhouse coverings and irrigation pipes.	• Macroplastic modelling. • Esperanza Huerta Lwanga et al., *Review of Microplastic Sources, Transport Pathways and Correlations With Other Soil Stressors: A Journey From Agricultural Sites Into the Environment*, 2022. • Ali Chamas et al., *Degradation Rates of Plastics in the Environment*, 2020. • Shams Forruque Ahmed et al., *Microplastic Removal and Management Strategies for Wastewater Treatment Plants*, 2024. • Pim van den Berg et al., *Sewage Sludge Application as a Vehicle for Microplastics in Eastern Spanish Agricultural Soils*, 2020, 261. • Martin Henseler, *Plastic Emissions From Mulch Film and Abatement Measures—A Model-Based Assessment for Germany*, 2022.

3.C. Scope of plastic life-cycle stages modelled

The BPW2 analysis estimates the stocks and flows of the modelled macroplastics and microplastics at various stages of the plastic life cycle. The macroplastic system map (Figure 3-1) identifies the modelled life-cycle stages as boxes. Inter-related life-cycle stages are connected to one another via arrows or “flows.” Each box is labelled with a unique letter or letter combination and a number that is used in Pathways. Each flow is labelled with both an alphanumeric string, in which the letter corresponds to the box from which it originates and the number identifies the number of flows emerging from that box, and a unique number that is used in Pathways. The boxes with bold outlines are “stocks” or points at which the quantity of modelled plastic accumulates. As shown in Figure 3-1, the modelled life-cycle stages are grouped into the following five modules: (1) Production, Consumption and Waste Generation; (2) Waste Collection and Sorting; (3) Recycling; (4) Disposal; and (5) Mismanagement of Waste.

Similarly, the microplastic system maps (Figure 3-2) detail the stocks and flows of each modelled microplastic type at various life-cycle stages. Each microplastic type has its own system map that details the scope of the life cycle modelled in BPW2. The system maps operate the same way as the macroplastic map. In cases where boxes are greyed out, this indicates either that there are known pathways for the microplastic source where data was unavailable to support explicit modelling, or that the life-cycle stage is not relevant for the specific microplastic source. For example, there is very limited data on the amount of synthetic textile microfibres lost to the air, so the boxes associated with textile microplastics lost to the air are greyed out in the textiles system map.

Figure 3-1. Macroplastic System Map

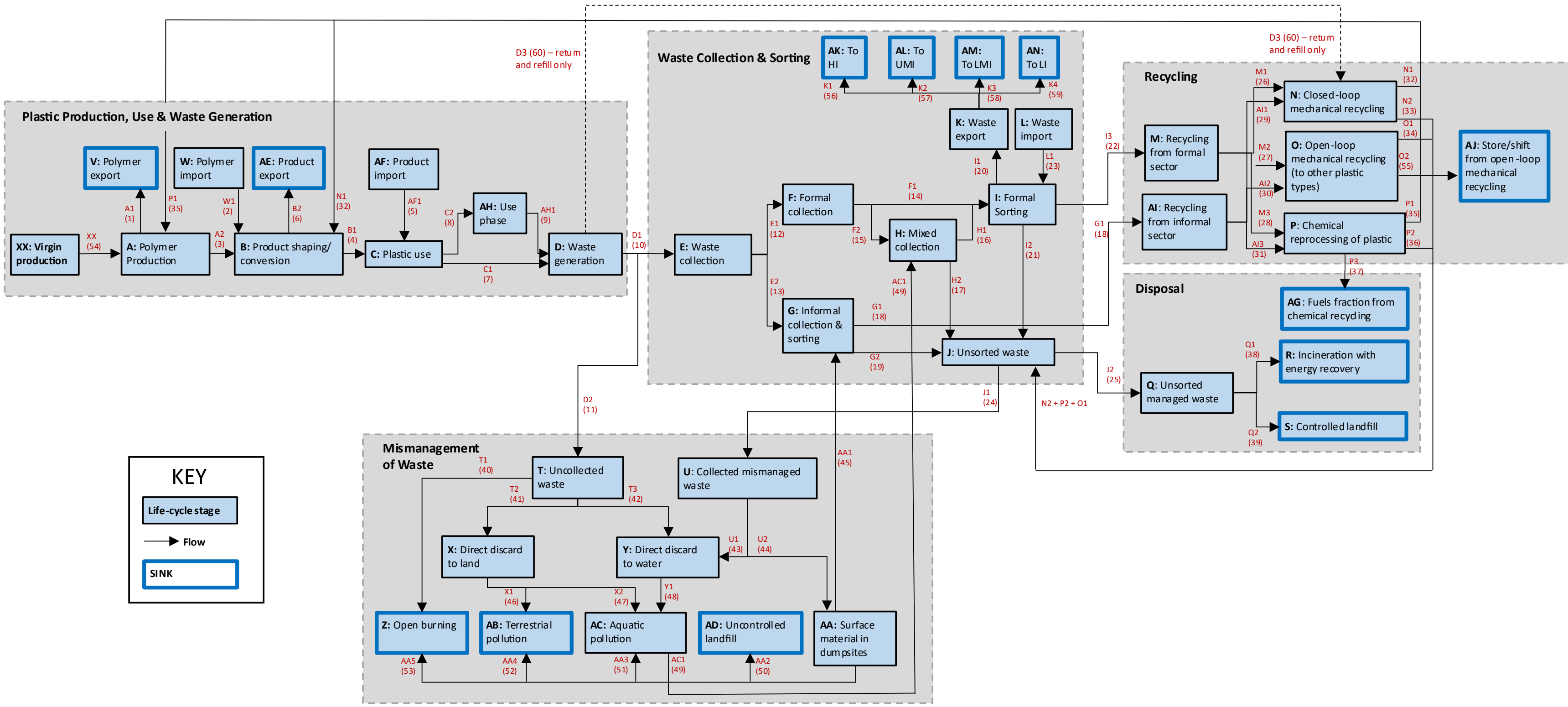
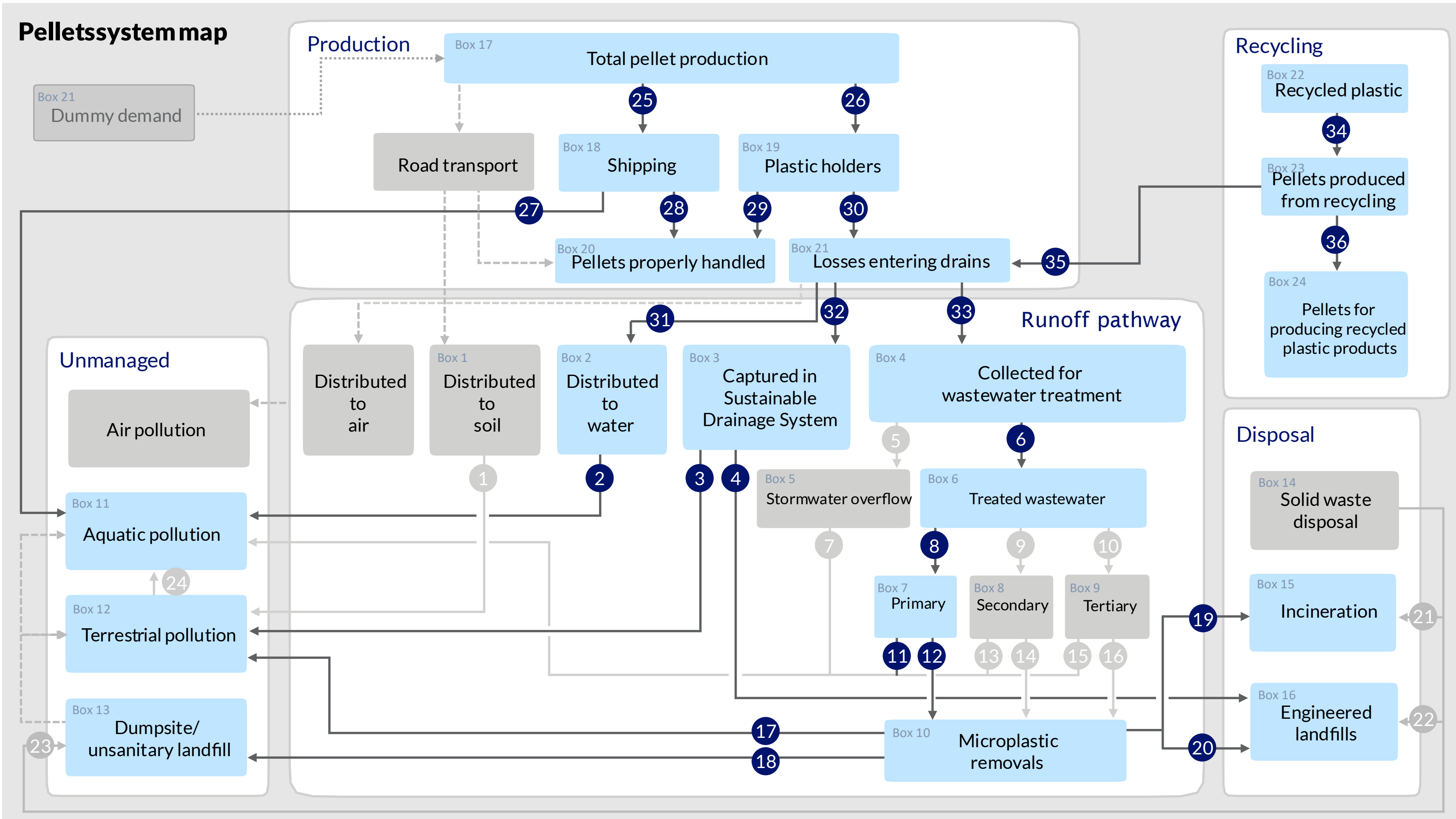
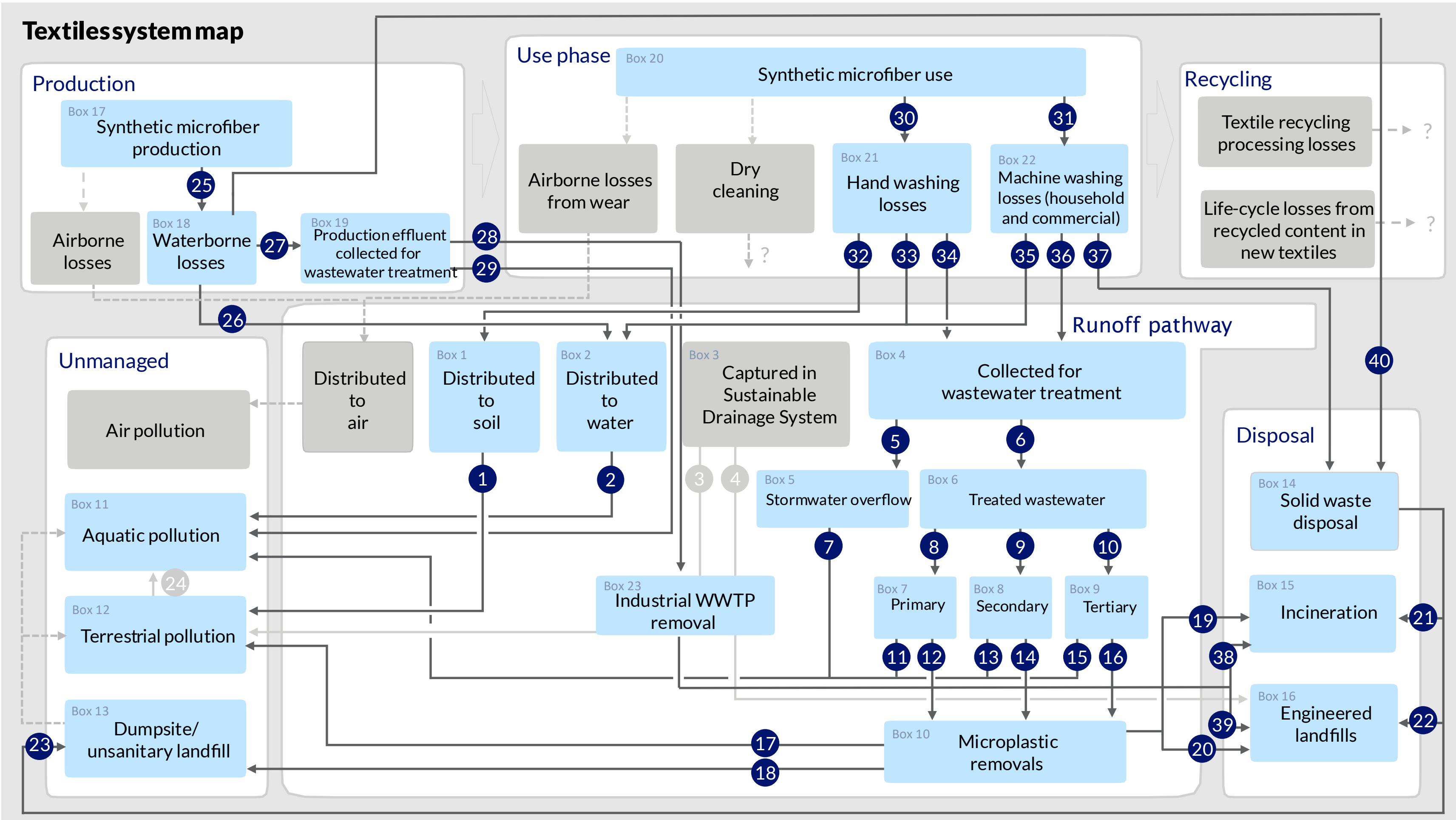


Figure 3-2. Microplastic System Maps

(a) Pellets

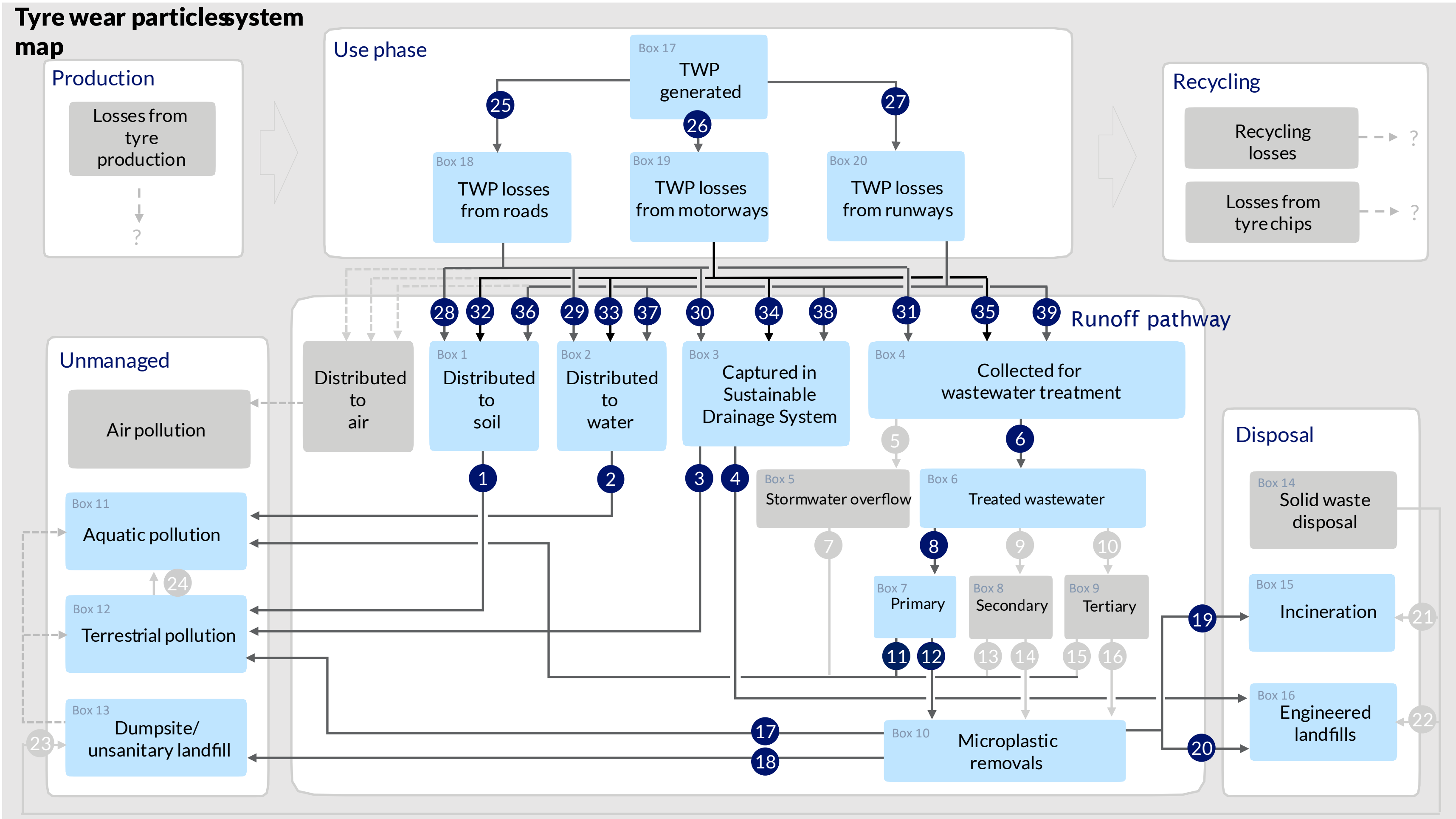


(b) Textiles



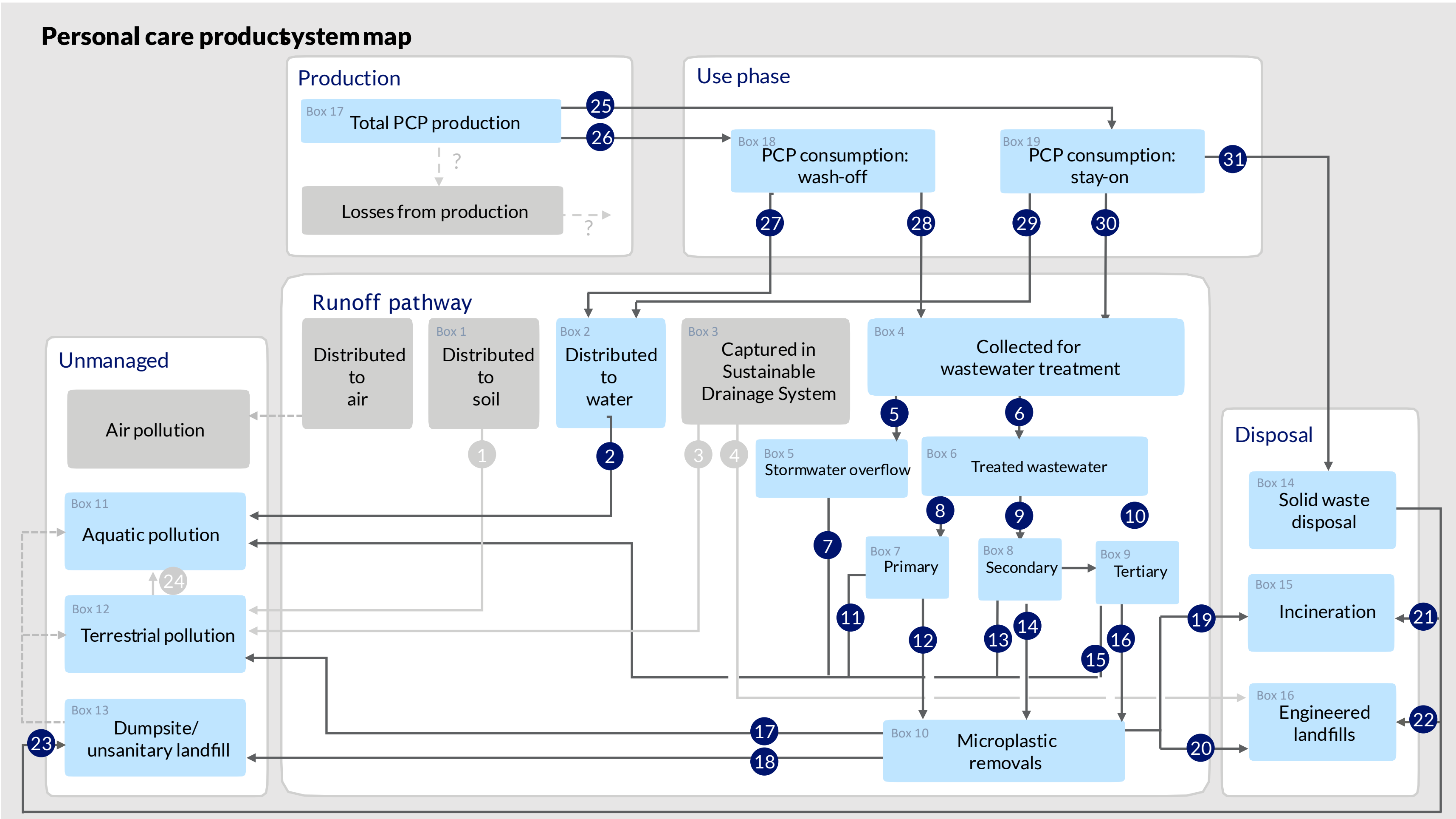
Textiles system map
Production
Box 17
Synthetic microfiber production
Airborne losses
Box 18
Waterborne losses
Box 19
Production effluent collected for wastewater treatment
Use phase
Box 20
Synthetic microfiber use
Airborne losses from wear
Dry cleaning
?
Box 21
Hand washing losses
Box 22
Machine washing losses (household and commercial)
Recycling
Textile recycling processing losses
?
Life-cycle losses from recycled content in new textiles
?
Runoff pathway
Unmanaged
Air pollution
Box 11
Aquatic pollution
Box 12
Terrestrial pollution
Box 13
Dumpsite/ unsanitary landfill
Distributed to air
Box 1
Distributed to soil
Box 2
Distributed to water
Box 3
Captured in Sustainable Drainage System
Box 4
Collected for wastewater treatment
Box 5
Stormwater overflow
Box 6
Treated wastewater
Box 23
Industrial WWTP removal
Box 7
Primary
Box 8
Secondary
Box 9
Tertiary
Box 10
Microplastic removals
Disposal
Box 14
Solid waste disposal
Box 15
Incineration
Box 16
Engineered landfills
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40

(c) Tyres

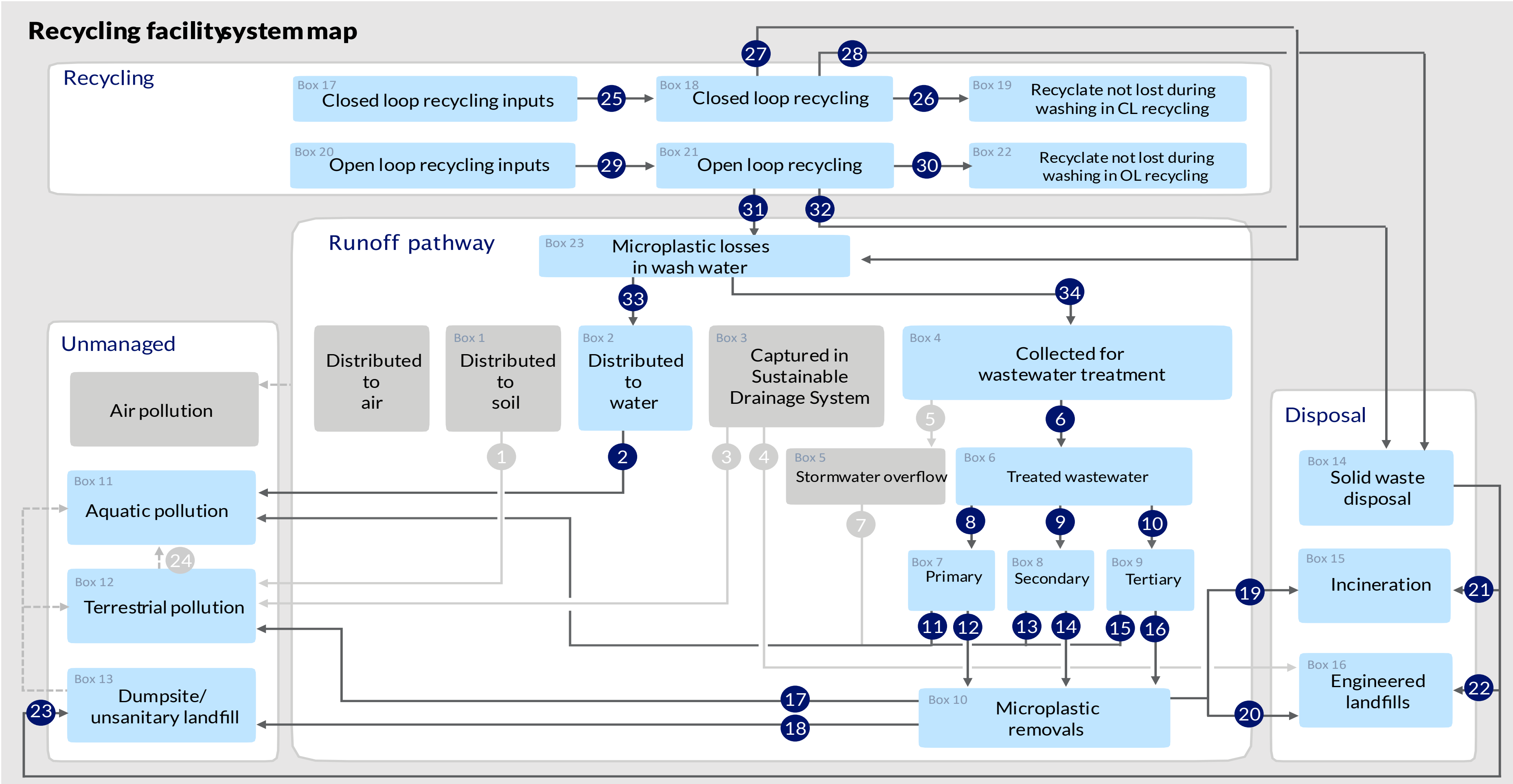


Tyre wear particles system map
Production
Losses from tyre production
?
Use phase
Box 17
TWP generated
25
26
27
Box 18
TWP losses from roads
Box 19
TWP losses from motorways
Box 20
TWP losses from runways
Recycling
Recycling losses
?
Losses from tyre chips
?
28
32
36
29
33
37
30
34
38
31
35
39
Runoff pathway
Unmanaged
Air pollution
Distributed to air
Box 1
Distributed to soil
Box 2
Distributed to water
Box 3
Captured in Sustainable Drainage System
Box 4
Collected for wastewater treatment
5
6
1
2
3
4
Box 5
Stormwater overflow
Box 6
Treated wastewater
Disposal
Box 14
Solid waste disposal
Box 11
Aquatic pollution
7
8
9
10
24
Box 7
Primary
Box 8
Secondary
Box 9
Tertiary
Box 15
Incineration
19
21
Box 12
Terrestrial pollution
11
12
13
14
15
16
Box 13
Dumpsite/ unsanitary landfill
23
17
18
Box 10
Microplastic removals
Box 16
Engineered landfills
20
22

(d) Personal care products

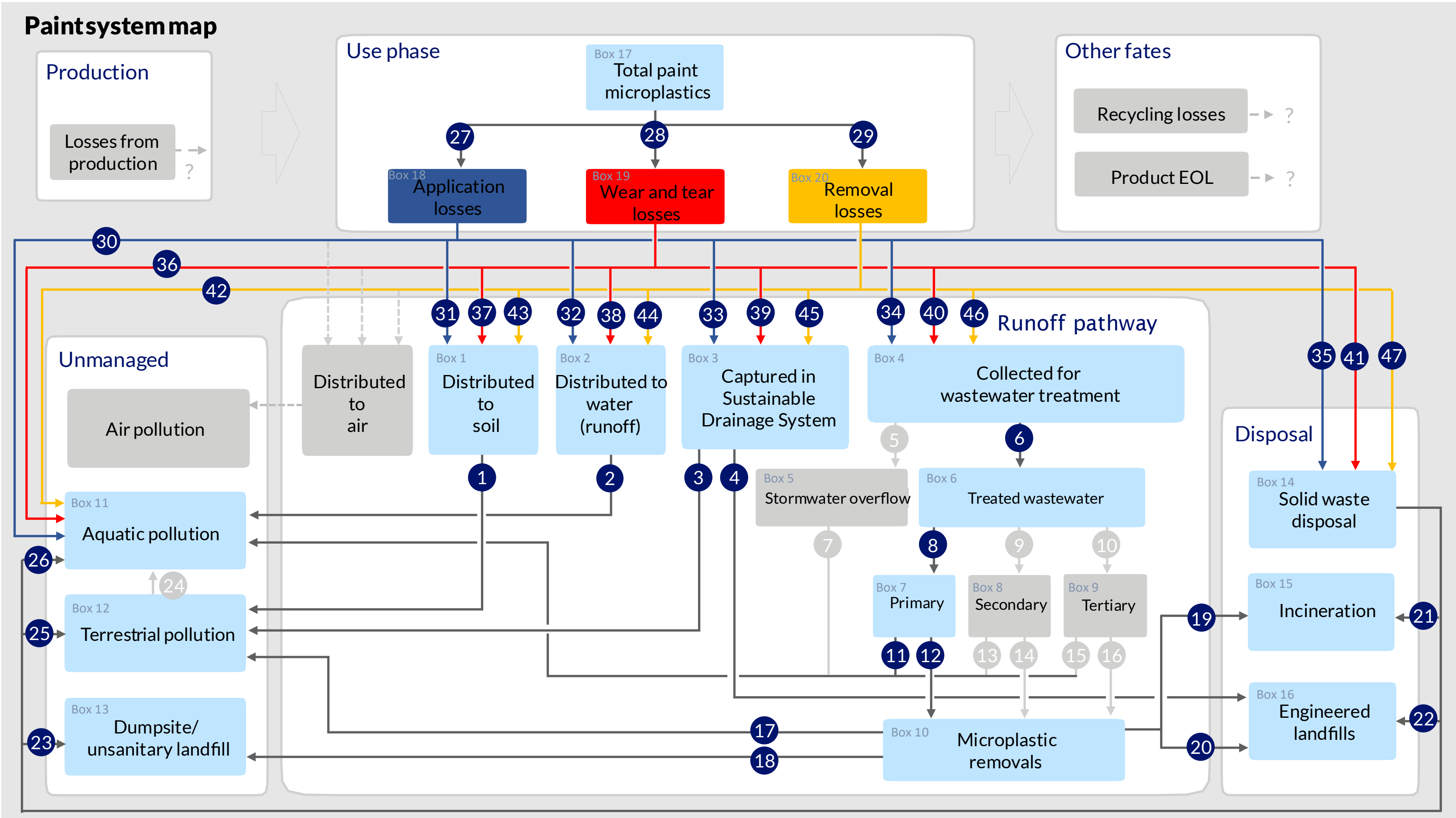


(e) Recycling

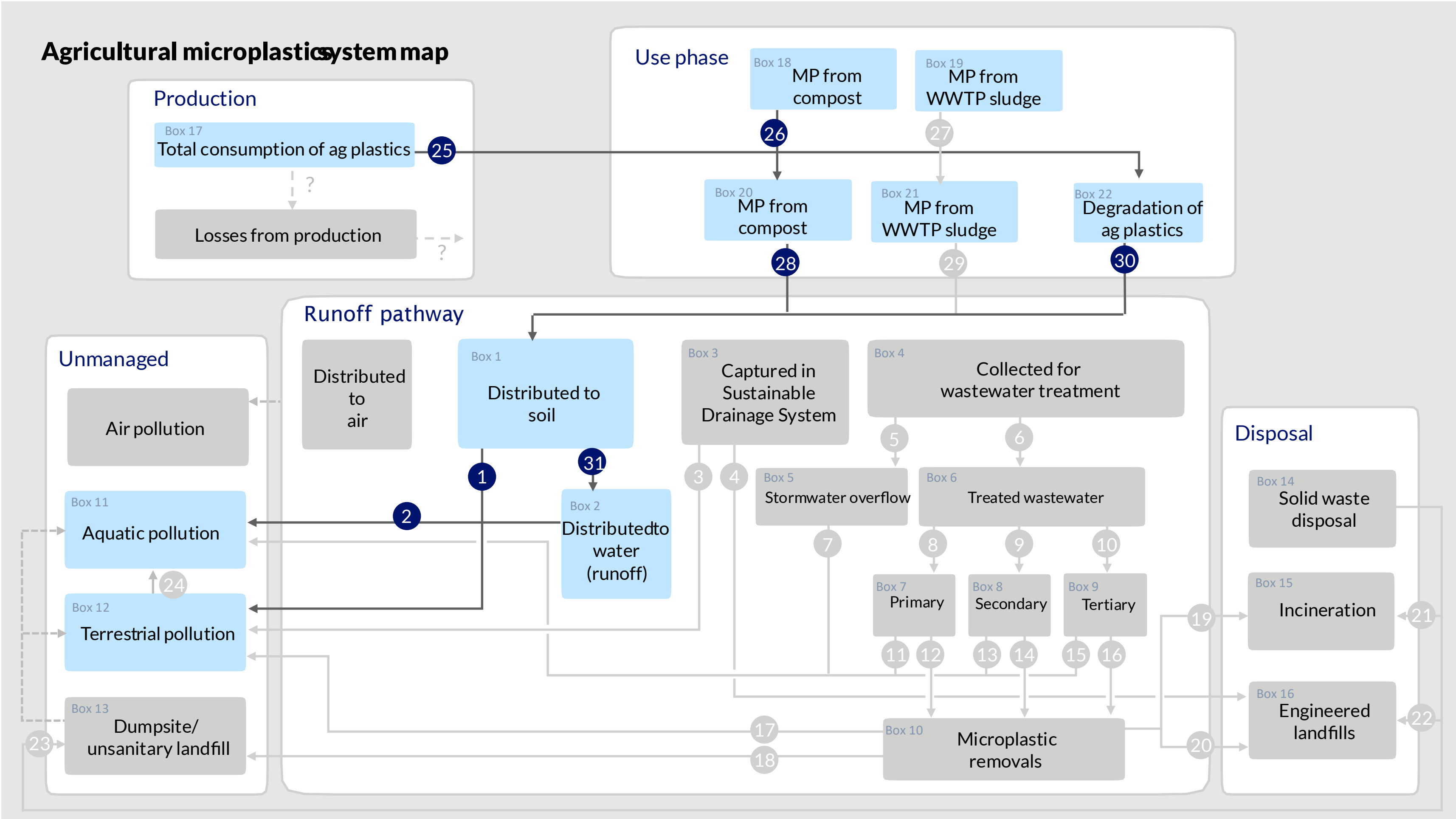


Recycling facility system map
Recycling
Box 17
Closed loop recycling inputs
25
Box 18
Closed loop recycling
26
Box 19
Recyclate not lost during washing in CL recycling
27
28
Box 20
Open loop recycling inputs
29
Box 21
Open loop recycling
30
Box 22
Recyclate not lost during washing in OL recycling
31
32
Runoff pathway
Box 23
Microplastic losses in wash water
33
34
Unmanaged
Air pollution
Distributed to air
Box 1
Distributed to soil
Box 2
Distributed to water
Box 3
Captured in Sustainable Drainage System
Box 4
Collected for wastewater treatment
1
2
3
4
5
6
Box 5
Stormwater overflow
Box 6
Treated wastewater
7
8
9
10
Box 11
Aquatic pollution
24
Box 12
Terrestrial pollution
Box 13
Dumpsite/ unsanitary landfill
23
Box 7
Primary
Box 8
Secondary
Box 9
Tertiary
11
12
13
14
15
16
17
18
Box 10
Microplastic removals
19
20
Disposal
Box 14
Solid waste disposal
Box 15
Incineration
21
Box 16
Engineered landfills
22

(f) Paint


Paint system map
Production
Losses from production
?
Use phase
Box 17
Total paint microplastics
27
28
29
Box 18
Application losses
Box 19
Wear and tear losses
Box 20
Removal losses
Other fates
Recycling losses
?
Product EOL
?
30
36
42
31
37
43
32
38
44
33
39
45
34
40
46
Runoff pathway
35
41
47
Unmanaged
Air pollution
Distributed to air
Box 1
Distributed to soil
Box 2
Distributed to water (runoff)
Box 3
Captured in Sustainable Drainage System
Box 4
Collected for wastewater treatment
5
6
1
2
3
4
Box 5
Stormwater overflow
Box 6
Treated wastewater
Disposal
Box 14
Solid waste disposal
Box 11
Aquatic pollution
26
24
7
8
9
10
Box 12
Terrestrial pollution
25
Box 7
Primary
Box 8
Secondary
Box 9
Tertiary
19
Box 15
Incineration
21
11
12
13
14
15
16
Box 16
Engineered landfills
22
Box 13
Dumpsite/ unsanitary landfill
23
17
18
Box 10
Microplastic removals
20

(g) Agriculture



3.D. Scope of impacts modelled

Table 3-7 identifies the categories of impacts modelled in BPW2 along with the key sources for data and assumptions.

Table 3-7. Impacts Modelled in BPW2 and Key Sources for Data and Assumptions

Impact category	Definition/scope	Key data sources
Health	The BPW2 analysis estimates human health impacts associated with plastic from certain stages of the plastic life cycle. The impacts are measured in disability-adjusted life years, a measure of the burden of disease that combines mortality and morbidity. For more information, please see section 5.A.	• Megan Deeney et al., *Global Health Impacts of Addressing the Plastic Pollution Crisis: A Life Cycle Approach*, 2023.
GHG emissions	GHG emissions associated with plastic production, waste management and end-of-life fates, measured in carbon dioxide equivalent (CO_2e), a metric used to standardize the climate effects of different GHGs by expressing them in terms of the amount of CO_2 that would cause the same warming effect. We apply two separate GHG emissions trajectories, one that reflects current emissions intensities across the plastic system and a second that reflects efforts to achieve net zero emissions by 2050 as modelled by the International Energy Agency (International Energy Agency, *World Energy Outlook 2024*, 2024).	• Nihan Karali, Nina Khanna, and Nihar Shah, *Climate Impact of Primary Plastic Production*, 2024 (production). • Megan Deeney et al., *Global Health Impacts of Addressing the Plastic Pollution Crisis: A Life Cycle Approach*, 2023 (collection, sorting, disposal, recycling, mismanagement). • United States Environmental Protection Agency, Office of Resource Conservation and Recovery, *Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM): Management Practices Chapters*, 2023 (substitutes). • Ellen MacArthur Foundation, *Unlocking a Reuse Revolution: Scaling Returnable Packaging*, 2023 (reuse).
Costs and revenues	Costs include both capital and operating expenditures and revenues include sales prices and tipping fees.	• Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020. • Felix Cornehl et al., *Plastic Treaty Futures: Assessing Alternative Scenarios for the Treaty*, 2024 (reuse, substitutes).

Direct employment	Employment estimates include jobs in both the formal and informal sectors.	• Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020. • Felix Cornehl et al., *Plastic Treaty Futures: Assessing Alternative Scenarios for the Treaty*, 2024. • Christiana Dujardin, email, June 19, 2025 (reuse, substitutes).

3.E. Comparing the BPW1 and BPW2 modelling scopes

BPW2 leverages new data and research published since the release of BPW1, as well as improvements and updates to Pathways. It significantly expands the modelling scope, increasing the coverage of plastic types, substitutes, impacts and life-cycle stages modelled. Table 3-8 provides a comparison of the key modelling parameters from BPW1 and BPW2. As described in the table, the plastic types modelled vary significantly between the two analyses, and therefore the modelling results are not directly comparable.

Table 3-8. Comparison of BPW1 and BPW2 Modelling Scopes

Modelling parameter	BPW1	BPW2
Modelling period	2016–2040	2021–2040
Geographic resolution	Eight geographic archetypes, including four income categories with urban-rural classifications for each	Eight geographic archetypes, including four income categories with urban-rural classifications for each
Macroplastic categories and resolution	Plastic in municipal solid waste, disaggregated into three categories: rigid monomaterials, flexible monomaterials and multilayer/multimaterials	Plastic from 10 sectors: agriculture, aquaculture, building and construction, consumer and institutional goods, electrical and electronics, fisheries, industrial and machinery, packaging, textiles and transportation
Microplastic categories	Microplastics from four sources: tyres, pellets, textiles and personal care products	Microplastics from seven sources: tyres, recycling, pellets, textiles, personal care products, paint and agriculture
Substitute materials	Paper, coated paper and compostables	Glass, metal, paper and compostables
Impacts analysed	Costs (capital and operating expenditures), direct employment and GHG emissions	Costs (capital and operating expenditures), direct employment, GHG emissions and health impacts

4. Methods for macroplastic Business as Usual scenario

BAU assumes no policy interventions are made relative to current plastic-related policy, economics, infrastructure, or materials and that cultural norms and consumer behaviours do not change. For European Union member States, the BAU includes estimated reductions in plastic use associated with recent commitments by the EU to reduce plastic packaging and packaging waste.[6] Specifically, the BAU phases out all multilayer packaging; all PS rigid food packaging; 25% of flexible PP, flexible HDPE, flexible LDPE and all other non-PS rigid food packaging; and 10% of all other packaging plastic.

BPW2 models three different BAU scenarios: (1) an "unconstrained" BAU, (2) a "constrained" BAU and (3) a "constrained" BAU with global decarbonization efforts.

4.A. Unconstrained BAU

In the unconstrained BAU scenario, the model allows plastic production and use to increase as forecasted and does not place any constraints on the ability of the system to manage the resulting waste. In reality, the waste management system faces capacity constraints, such as limits on waste collection, recycling, landfills and incineration. However, the purpose of this scenario is to model a future in which the waste management system can scale with projected increases in plastic production and use.

4.B. BAU with constraints

In the constrained BAU, the model places limits, or "constraints," on various flows in the system map to define how much plastic waste can move through a given box in a given year. The purpose of this scenario is to model a future in which the waste management system cannot accommodate the increasing plastic production and use at scale and is instead limited in terms of the amount of waste that can be collected and enter landfills, incinerators and recycling facilities each year.

In Pathways, constraints on a given box (e.g., formal collection) are specified as a percentage of the mass entering the box in the first year. The model then applies an annual growth rate to this initial mass constraint. The constraints used in BPW2 were determined using expert elicitation. Growth rates for formal collection, mechanical recycling and managed disposal were calculated based on average GDP per capita growth in each archetype between 2022 and 2023.[7] Growth rates for chemical recycling are based on projected growth rates for chemical recycling industry set to half the average GDP per capita growth from 2022 to 2023. Growth rates for informal collection are calculated based on population growth for each archetype with the assumption that a certain proportion of an archetype's population would enter or exit as waste pickers. When the constraints on the boxes are met, the mass gets shifted to a specified "overflow" box. For total collection and formal collection, if the constraint is hit, the extra mass gets shifted to uncollected waste (box 27). For formal collection, mechanical recycling and chemical recycling constraints, if the constraint is hit, the extra mass is shifted to unsorted waste (box 17). For managed disposal, if the constraint is hit, the extra mass is shifted to collected mismanaged waste (box 28). Table 4-1 shows the values used for each throughput constraint.

Table 4-1. BAU Box Throughput Constraints

Box	% of Year 1	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
11 (formal collection)	100	1.750	1.750	3.650	3.650	4.2	4.20	0.650	0.650
12 (informal collection)	100	0.410	-1.310	0.750	-1.890	2.2	-0.07	3.730	1.340

Box	% of Year 1	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
20 (closed-loop mechanical recycling)	200	1.750	1.750	3.650	3.650	4.2	4.20	0.650	0.650
21 (open-loop mechanical recycling)	200	1.750	1.750	3.650	3.650	4.2	4.20	0.650	0.650
22 (chemical recycling)	100	0.875	0.875	1.825	1.825	2.1	2.10	0.325	0.325
23 (unsorted managed waste)	125	1.750	1.750	3.650	3.650	4.2	4.20	0.650	0.650

4.C. BAU with constraints and decarbonization

The BAU with constraints and decarbonization includes the constraints outlined above, as well as ambitious decarbonization of the plastic sector. The purpose of this scenario is to model a future in which emissions from various stages of the plastic life cycle are decreased as a result of global decarbonization efforts. The assumptions underlying the decarbonization scenario are based on International Energy Agency "World Energy Outlook" data on different industries' trajectories to net zero emissions by 2050.[8] For life-cycle emissions where the split between emissions coming from industrial heating, electricity and transportation is unknown, decarbonization rates for electricity are applied. Where the split is known, the share of emissions from each source is decarbonized according to the different decarbonization rates from each source. Table 4-2 provides the decarbonization rates for each emission source, as applied in the scenario.

Table 4-2. Decarbonization Rates

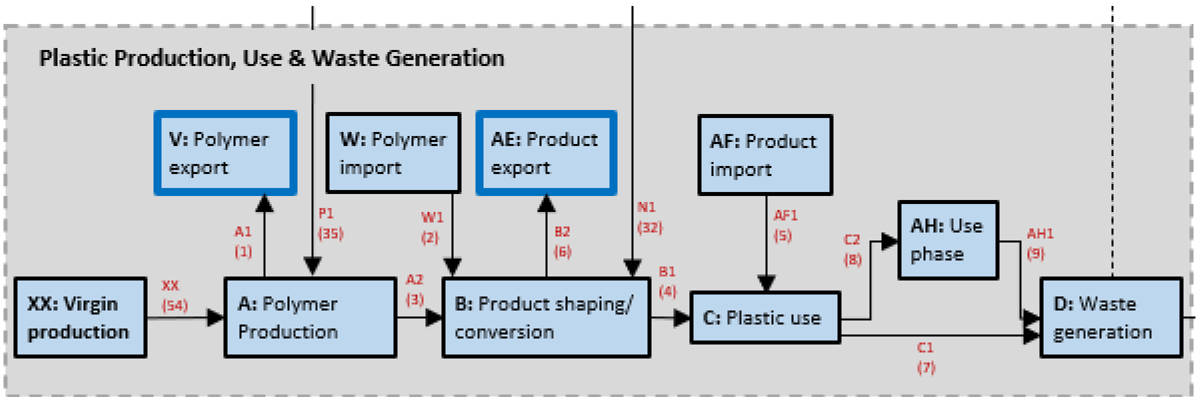
Emissions source	Time frame	Compound annual growth rate
Industrial heating	2021–2030	-3.56%
Industrial heating	2031–2035	-5.69%
Industrial heating	2036–2040	-8.01%
Industrial heating	2041–2050	-19.71%
Transport	2021–2030	-3.71%
Transport	2031–2035	-5.78%
Transport	2036–2040	-8.44%
Transport	2041–2050	-14.93%
Electricity	2021–2030	-10.70%
Electricity	2031–2035	-23.70%
Electricity	2036–2040	-41.25%
Electricity	2041–2050	-100.00%

4.D. Production, Use and Waste Generation Module

Figure 4-1 depicts the boxes and flows comprising the Production, Use and Waste Generation Module. This module calculates the mass of plastic flowing through two primary production stages

– polymer production (box A) and product shaping/conversion (box B) – and the mass of plastic used (box C) by geographic archetype, plastic type and year. It differentiates the mass of plastic coming from virgin material production (flow 54) and from recyclate (flows 32 and 35, which come from the Recycling Module). This module also calculates imports and exports of polymers (flows 2 and 1, respectively) and products (flows 5 and 6, respectively). Finally, it calculates plastic mass retained in the use phase (box AH) and plastic mass that becomes waste (box D).

Figure 4-1. Production, Consumption and Waste Generation Module



4.D.1. Plastic use

Plastic use estimates are the starting point for the mass flow calculations. Total plastic use by archetype, plastic type and year are inserted into the modelling input sheets as flow 54 and Pathways then calculates virgin plastic production based on the values of polymer and product imports and exports and recycling flows.

a) Primary estimates

For most plastic types, the growth in plastic use is projected from the Organisation for Economic Co-operation and Development's (OECD's) computable general equilibrium (CGE) model, ENV-Linkages, as a combination of population growth, economic growth and technological change.[9] BPW2's global plastic use projections are based on the following publicly available OECD data sets from its "Global Plastics Outlook":

- For the year 2019, a complete data set providing estimates of plastic use by region, sector and polymer.[10]
- For the years 2019 to 2060, a data set that lists total annual regional plastic use, global total annual polymer plastic use and global total annual sector plastic use.[11]

We developed our projections of plastic use through 2040 by calculating regional growth rates in plastic use from the Plastic Use Projections data set and applying them to the baseline data.[12] We assume that the relative distribution of plastic use across polymers and sectors within each region remains constant over time. Table 4-3 lists the specific dimensions for both OECD data sets. We transformed the OECD region estimates to country-level estimates for most of the data processing before aggregating the flows to the archetype level used in the model. We estimated country-level use by calculating per capita use rates based on OECD region population and applying those per capita rates to country-level population estimates from 2021 to 2040.

Table 4-3. Dimensions of OECD Plastic Use Data

Regions	Economic sectors	Polymers
• Australia and New Zealand • Canada • People's Republic of China • European Union countries in OECD • European Union non-OECD countries • India • Latin America • Middle East and North Africa • Non-European Union countries in OECD • OECD Asia • Other Africa • Other Asia • Other non-OECD Eurasia • Other OECD America • United States of America	• Building & construction • Consumer & institutional products • Electrical/electronics • Industrial/machinery • Packaging • Textiles • Transportation – other • Transportation – tyres	• Acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate (ASA), styrene acrylonitrile (SAN) • Bioplastics • Elastomers (specific for transportation – tyres) • HDPE • LDPE, LLDPE • Other • PET • PP • PS • Polyurethane (PUR) • PVC

Notes: For example countries within each of the listed regions, see Organisation for Economic Co-operation and Development, *Global Plastics Outlook: Policy Scenarios to 2060*, 2022, Table A.2, Regional Aggregation of ENV-Linkages. For the purposes of modelling in BPW2, the following polymers defined in the OECD data were combined into an "other" category in our analysis: ABS, ASA, SAN, bioplastics, other and PUR.

We transform the OECD region estimates to country-level estimates for most of the data processing before aggregating the flows to the archetype level used in the model. We estimate country-level use by calculating per capita use rates based on UN population projections for OECD regions and applying those per capita rates to country-level population estimates from 2021 to 2040.[13] These country-level use estimates are then aggregated to the income level (HI, UMI, LMI and LI) based on each country's World Bank income level in 2024. The assigned income level is then maintained over the course of the modelling period. In other words, we do not account for the possibility that individual countries could move between income classes over time.

We distribute plastic use to urban and rural areas within an income level according to assumptions from BPW1 regarding the ratio of waste generation between urban and rural areas. Table 4-4 shows the ratios used. These ratios indicate that, for example, at the LMI income level, urban areas use 1.5

metric tons of plastic for every metric ton rural areas use. These values are applied by creating a rural consumption scale using the following equation:

$$consumption\_scale_{rural} = \frac{1}{(\%pop_{rural} + (\%pop_{urban} * ratio_{urban}))}$$

where

$\%pop_{rural}$ is the percentage of the population in an archetype that lives in rural areas,

$\%pop_{urban}$ is the percentage of the population in an archetype that lives in urban areas, and

$ratio_{urban}$ is the urban ratio value found in Table 4-4.

After the rural consumption scale is created, it is multiplied by the per capita plastic use value previously created for the income archetype to provide rural per capita plastic use. Rural per capita plastic use is then multiplied by the urban ratio value to yield urban per capita plastic use. This same method is applied to production, conversion, polymer imports and exports and plastic goods imports and exports.

Table 4-4. Ratio of Waste Generation in Rural Areas to Urban Areas

	HI	UMI	LMI	LI
Urban	1	1.2	1.5	2
Rural	1	1.0	1.0	1

Source: Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020

BPW2 uses a variety of other data sources for the economic sectors not explicitly covered by the OECD "Global Plastics Outlook" (agriculture, aquaculture and fisheries) and for which we had targeted data (textiles).

b) Agriculture

BPW2 projects annual plastic use in the agriculture sector based on U.N. Food and Agriculture Organization (FAO) country-level agricultural production in 2021 and Gilbert, Ricci and Thompson 2021's estimates of the tonnage of durable (long-term) and non-durable (short-term) plastic used in agriculture (Table 4-5).[14] While this data is likely referring to 2018 agricultural plastic use, we assume the same plastic use for 2021. From these values, we estimate a global ton of plastic used per ton of agricultural product produced rate that we apply uniformly to the country-level agricultural production values. This yields agricultural plastic use by country in 2021. We then use estimated regional growth rates in agricultural plastic use from Le Moine and Ferry, 2019, to project annual plastic use in agriculture from 2021 to 2040 (Table 4-6).[15]

Table 4-5. Total Global Plastic Use in Agriculture

Product type breakdown	Annual global production (t)	Typical lifespan (months)
Durable agricultural plastic (greenhouse films, some non-films)	4,750,000	45
Non-durable agricultural plastic (mulch films, silage films, pesticide containers, some non-films)	5,550,000	6

Note: Durable plastic equals the sum of greenhouse films and half of non-films. Non-durable is the sum of all other agricultural plastic.

Source: Jane Gilbert, Marco Ricci, and Richard H. Thompson, Assessment of Agricultural Plastics and Their Sustainability: A Call for Action, 2021, Figure 10

Table 4-6. Agricultural Plastic Use Growth Rates From 2017 to 2030 and Corresponding Compound Annual Growth Rate

Region	Growth from 2017 to 2030	Compound annual growth rate
Asia	64%	3.9%
Europe	16%	1.1%
North America	12%	0.9%
Africa	51%	3.2%
South America	71%	4.2%

Note: The calculated compound annual growth rate is applied through 2040 to both short-term and long-term plastic.

Source: B. Le Moine and X. Ferry, Plasticulture: Economy of Resources, 2019

c) Aquaculture and fisheries

Plastic use in the aquaculture and fisheries sectors is estimated based on gear-to-catch ratios and FAO country-level catch data.[16] Table 4-7 presents the assumed gear-to-catch ratios. Table 4-8 and Table 4-9 present the estimated growth rates in fishery and aquaculture captures from.[17]

For fisheries, we apply plastic gear-to-catch ratios from the Nordic Council to country-level plastic use fisheries catch data (provided by the FAO) to estimate the amount of plastic fisheries gear used by country.[18] We then calculate compound annual growth rates for the growth in fisheries capture (as provided by FAO) to project plastic fisheries gear use from 2021 to 2045. We use the same methods for aquaculture plastic gear.

Similar to the other plastic sectors, we aggregate country-level plastic use to the income archetype level. We assume that plastic in these sectors is only used in rural archetypes. We also assume that this plastic is produced and used within the same archetype, meaning there are no imports or exports of polymers or products in these sectors.

Table 4-7. Plastic Fishing Gear-to-Catch Ratios

Plastic type	Assumed ratio of plastic fishing gear to catch
Capture fisheries (global total)	4.2%
Aquaculture (global total)	1.3%

Source: Systemiq, Towards Ending Plastic Pollution by 2040: Technical Annex, 2023

Table 4-8. Regional Capture Fisheries Growth Rates

Region	Growth between 2022 and 2032
Africa	6.9%
North America	5.7%
Latin America and Caribbean	7.6%
Asia	0.8%
Europe	3.8%
Oceania	0.4%

Source: Food and Agriculture Organization of the United Nations, *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*, 2024, Table 14

Table 4-9. Regional Aquaculture Growth Rates

Region	Growth between 2022 and 2032
Africa	21.4%
North America	2.9%
Latin America and Caribbean	13.7%
Asia	17.9%
Europe	9.0%
Oceania	17.3%

Source: Food and Agriculture Organization of the United Nations, *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*, 2024, Table 14

d) Textiles

For the textiles sector, BPW2 estimates plastic use from global synthetic textile production data.[19] We project global synthetic textile production using a combination of total textile production estimates through 2040 (Table 4-10) and estimates about the share of total textile production that are synthetic materials (Table 4-11). We estimate textile trade between producers and consumers (flows 5 and 6 in the model) based on the difference between our estimates of archetype-level production and use.[20] We estimate synthetic textile use by distributing total synthetic textile production to the appropriate archetypes using OECD textile use data from the "Global Plastics Outlook" (Table 4-13).

BPW2 calculates archetype textile production using data from World Trade Organization, 2023, the top 10 textile exporters in 2010 and 2022.[21] These country-level shares of textile exports are converted to income-level averages. Table 4-12 shows the calculated shares in production in 2021 and 2040. We assume the low-income archetype has negligible textile production.

The share of textiles that are synthetic textiles is also pulled from the Textile Exchange and growth is projected.[22] Global synthetic textile production from 2021 to 2045 is estimated by multiplying projected global textile production by the projected share of textiles that is synthetic. This global production is then distributed to archetypes and rural/urban zones by multiplying total global synthetic production by archetype production share from Boucher and Friot, 2017.[23] These values are then portioned to urban and rural areas by the share of population within each archetype that falls into each zone. This synthetic textile production by archetype is used as an input to the macroplastic model for the textile plastic type.

Table 4-10. Total Textile Production

Total textile production in 2020 (t)	Compound annual growth rate
109,000,000	4%

Source: Textile Exchange, *Materials Market Report 2024*, 2024

Table 4-11. Share of Textile Production That Is Synthetic

Archetype	Share of textiles that are synthetic in 2017	Compound annual growth rate
HI	48.2%	0.2%
UMI, LMI, LI	68.0%	0.2%

Note: Compound annual growth rate in the share of textiles that are synthetic is calculated from Boucher and Friot's estimate of 4% growth by 2040.

Source: Julien Boucher and Damien Friot, Primary Microplastics in the Oceans: A Global Evaluation of Sources, 2017

Table 4-12. Estimated Income-Level Share of Textile Production

Archetype	2021	2040
HI	33.9%	29.8%
UMI	49.6%	53.6%
LMI	16.5%	16.6%

Note: Calculations based on textile exporter data from the World Trade Organization.

Source: World Trade Organization, World Trade Statistical Review 2023, 2023

Table 4-13. Archetype-Level Synthetic Textile Use Share

Archetype	Share of textile use in 2021	Share of textile use in 2040
HI-U	30.4%	25.5%
HI-R	6.9%	4.2%
UMI-U	24.0%	24.8%
UMI-R	10.3%	6.1%
LMI-U	13.2%	21.6%
LMI-R	12.9%	14.8%
LI-U	1.2%	1.9%
LI-R	1.1%	1.1%

Note: Calculations based on use data from the Organisation for Economic Co-operation and Development.

Source: Organisation for Economic Co-operation and Development, Global Plastics Outlook, 2019

e) Disaggregating packaging and consumer and institutional products into polymers and products

BPW2 disaggregates sector-level use data from OECD for packaging and consumer and institutional products using Minderoo's "Plastic Waste Makers Index" and Plasteax data, along with a variety of other sources on product-polymer shares provided by the BPW2 Expert Panel.[24]

We separated packaging sector plastic use into product categories using the Plasteax data set from Gallato, 2024.[25] The Plasteax data set contains data from 70 countries' total waste generated by packaging product type. Globally, we sum the mass for each product and divide it by global packaging mass to identify the share of each product within the overall packaging sector. BPW2 combines this breakdown, shown in Table 4-14, with the polymer shares within products, shown in Table 4-15, to disaggregate the packaging use data provided by OECD. We estimate polymer shares by product type using the sources listed in Table 4-14. For each product type, we averaged the share of each polymer across the various sources and standardized by product type, so each product's polymer composition summed to 100%. While these sources primarily report data from the U.S., U.K., EU and Canada, BPW2 assumes that the polymer composition of packaging product types is equivalent globally due to a lack of data from other countries.

Table 4-14. Share of Product Type Within the Packaging Sector

Sector	Product	Format	Product share
Packaging	Flexible packaging	Flexible	32.7%
Packaging	Multilayer packaging	Flexible	4.3%
Packaging	Other bottles	Rigid	8.9%
Packaging	PET bottles	Rigid	18.5%
Packaging	Rigid food packaging	Rigid	17.7%
Packaging	Rigid non-food packaging	Rigid	18.0%

Source: Martina Gallato, personal communication, 2024. EA – Earth Action, *Plasteax*

Table 4-15. Packaging Product Type Polymer Shares

Product type	Format	HDPE	PP	PET	Other*	PS†	PVC	LDPE‡
Flexible packaging	Flexible	6.7%	21.6%	4.8%	13.5%	1.0%	0.6%	51.8%
Multilayer packaging	Flexible	0.0%	4.3%	10.6%	12.4%	0.0%	3.7%	69.0%
Other bottles	Rigid	53.6%	3.8%	39.1%	0.0%	0.0%	0.2%	3.3%
PET bottles	Rigid	15.7%	0.9%	83.3%	0.0%	0.0%	0.0%	0.0%
Rigid food packaging	Rigid	10.9%	39.6%	35.5%	5.7%	6.3%	0.2%	1.7%
Rigid non-food packaging	Rigid	43.0%	32.0%	14.2%	1.6%	5.9%	0.3%	3.0%

* Other includes polymers such as PUR, ABS, SAN, PBT, PC, PMMA, PTFE and other mixtures of polymers.
† PS includes EPS.
‡ LDPE includes LLDPE.

Table 4-16. Packaging Polymer Share Sources

Source	Data contribution
Agnes Chruszcz and Sam Reeve, *Composition of Plastic Waste Collected via Kerbside*, 2018	PET bottle polymer composition Other bottle polymer composition Rigid food packaging polymer composition
LRS Consultancy, *WRAP Plastics Compositional Analysis at MRFs*, 2015	Rigid food packaging polymer composition
Anelia Milbrandt et al., *Quantification and Evaluation of Plastic Waste in the United States*, 2022	Flexibles polymer composition
Martijn Roosen et al., *Detailed Analysis of the Composition of Selected Plastic Packaging Waste Products and Its Implications for Mechanical and Thermochemical Recycling*, 2020	PET bottle polymer composition Multilayer packaging polymer composition
Marie Kampmann Eriksen and Thomas Fruergaard Astrup, *Characterisation of Source-Separated, Rigid Plastic Waste and Evaluation of Recycling Initiatives: Effects of Product Design and Source-Separation System*, 2019	PET bottle polymer composition Other bottle polymer composition Rigid food packaging polymer composition Rigid non-food packaging polymer composition
John Laurence Esguerra et al., *Characterization, Recyclability, and Significance of Plastic Packaging in Mixed Municipal Solid Waste for Achieving Recycling Targets in a Swedish City*, 2024	Flexibles polymer composition Rigid non-food packaging polymer composition
Giorgia Faraca and Thomas Astrup, *Plastic Waste From Recycling Centres: Characterisation and Evaluation of Plastic Recyclability*, 2019	Rigid food packaging polymer composition Rigid non-food packaging polymer composition Flexibles polymer composition
Griff Palmer and Thomas Baker, *Plastic Market Situation Report 2022*, 2023	Other bottle polymer composition Flexibles polymer composition Rigid food packaging polymer composition Rigid non-food packaging polymer composition

For consumer and institutional products, we identified the share of rigid and flexible and share of each polymer from the data provided on production and conversion in the Minderoo "Plastic Waste Makers Index."[26] Given the incomplete coverage of the data, we assume that PVC and PP are half rigid and half flexible for consumer and institutional products. We also assume that there is no PET or flexible HDPE for consumer and institutional products. Table 4-17 documents these assumptions. We use these values to disaggregate OECD's consumer and institutional polymer use masses by format.

Table 4-17. Share of Polymer Format for Consumer and Institutional Products Sector

Polymer	Flexible	Rigid
HDPE	0%	100%
LDPE	100%	0%
Other	0%	100%
PP	50%	50%
PS	0%	100%
PVC	50%	50%

4.D.2. Virgin production

Virgin plastic production – shown as flow 54 in the system map – is calculated for each plastic type and archetype and is derived based on plastic use, accounting for the share of use that comes from recyclate and imports. The model calculates flow 54 based on the following equation:

$$\begin{aligned} Virgin\ material\ demand \\ &= Use - Recyclate_{mech} - Recyclate_{chem} - Import_{poly} - Import_{good} \\ &+ Export_{poly} + Export_{good} \end{aligned}$$

This is performed iteratively over the course of the modelling time frame.

4.D.3. Conversion, imports and exports

We specify flows 1 through 6 based on Minderoo's data on plastic product shaping and trade from its "Plastic Waste Makers Index."[27] This data is specific to the packaging and consumer and institutional products sectors and covers both polymer trade and finished goods trade. It is provided at the country level by polymer. Given data gaps in the "Plastic Waste Makers Index," we assume that PVC and "other" polymers are produced, converted and used all within the same country.

For all other sectors, we estimate the amount produced, converted and imported/exported for a specific country using the country's production to use and conversion to use ratios from the packaging and consumer and institutional products sectors (the same is done for polymer and goods imports and exports). The use masses of the other sectors are multiplied by those ratios to get production, conversion and trade values. After this stage, all values are scaled so that global trade imports and exports are equal and that country-level production, conversion and use values balance globally with trade. The same methods are applied for all projected years. This assumes that the production and trade landscape will remain the same from 2021 to 2040.

4.D.4. Use phase and waste generation

BPW2 uses the average lifespans of plastic in different sectors and associated half-lives accomplished by assigning a half-life to the different plastic sectors.[28] These half-lives represent the "degradation rate" at which waste leaves the use phase (box AH) and enters the waste stream. The model calculates an initial "in-use" mass, so the box is at an equilibrium when the model starts. This ensures that we capture plastic entering the waste stream annually from plastic that entered the in-use phase prior to the start of our model.

Table 4-18. Average Lifespan of Plastic Sectors

Plastic sector	Mean lifespan (years)	Half-life
Packaging	1	0.69
Agriculture, short term	1	0.69
Consumer and institutional products	3	2.08
Agriculture, long term	3	2.08
Aquaculture	3	2.08
Fisheries	3	2.08
Transportation – tyres	4	2.77
Textile sector	5	3.47
Electrical/electronics	8	5.55
Transportation – other	13	9.01
Industrial/machinery	20	13.86
Building and construction	35	24.26

Sources: Roland Geyer, Jenna R. Jambeck, and Kara Lavender Law, *Production, Use, and Fate of All Plastics Ever Made*, 2017, 3. Habiba Afrin, Nazmul Huda, and Rouzbeh Abbasi, *Study on End-of-Life Tires (ELTs) Recycling Strategy and Applications*, 2021, 1200. Jane Gilbert, Marco Ricci, and Richard H. Thompson, *Assessment of Agricultural Plastics and Their Sustainability: A Call for Action*, 2021

4.D.5. Substitute waste generation

BPW2 also models the baseline masses of substitute materials flowing through the waste management system to achieve a more realistic model of when constraints on collection and disposal systems may be met. We use country-level material composition data from "What a Waste 2.0" to estimate the tons per year for glass, metal, paper and compostable materials.[29] We convert this to per capita waste generation by material and use only estimates of population growth to project future substitute material consumption in the BAU. We assume all waste generated is produced and used in the same archetype.

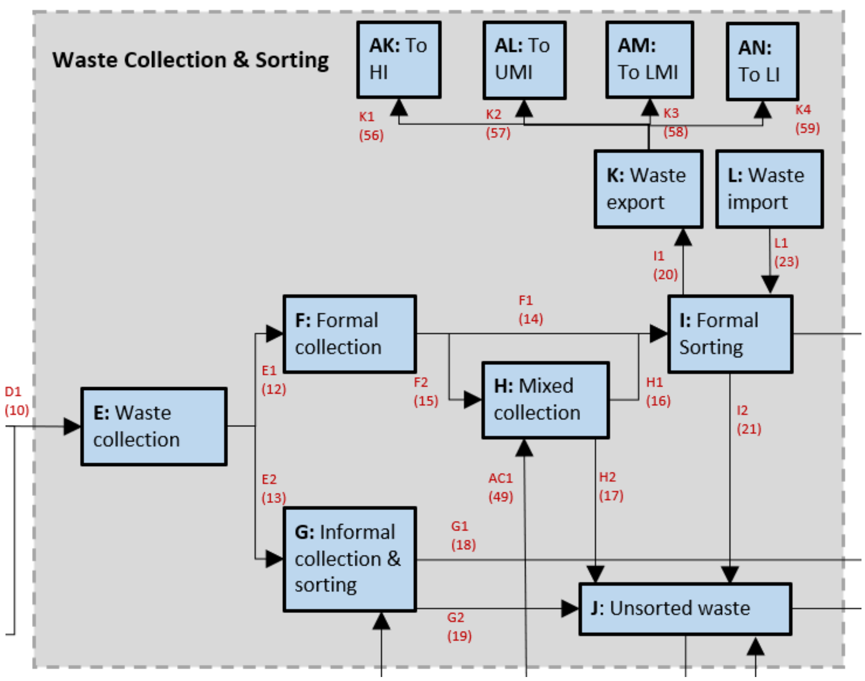
The return and refill material types do not have any mass under the BAU. The model assumes that any return or refill systems currently operating are captured in the BAU macroplastic and substitutes data. The return and refill material types will capture where mass from the BAU shifts to under various policy scenarios.

4.E. Waste Collection and Sorting Module

Figure 4-2 shows the flows in the Waste Collection and Sorting Module. This module calculates the amount of material mass flowing through three major processes – collection (boxes E, F and G), sorting for recycling or disposal (boxes H, I and J) and the export or import of waste (boxes K, L, AK, AL, AM and AN). This module includes the distribution of collection across formal and informal collection by archetype, as well as where exported waste is sent by archetype. All mass leaving this module is either recycled, sent to managed disposal, or mismanaged.

BPW2 estimated many of the flows in this module and the Disposal Module from the SPOT model, a GIS-based model for highlighting hot spots of plastic pollution.[30] BPW2 uses the municipal-level output data from this model and then aggregates to the BPW2 archetypes to estimate our archetype-level flows. Each municipality in the SPOT model was assigned a "degree urban" variable on a scale of 1 to 3. For the purposes of BPW2, any municipality with a ranking of 2 or 3 was assigned as an "urban" municipality, while those with a ranking of 1 were assigned a "rural" municipality. This enabled us to sum masses of the variables we used from the SPOT model for each flow to the archetype level while preserving the differences in the waste management system between urban and rural areas.

Figure 4-2. Waste Collection and Sorting Module



4.E.1. Collection

For all sectors except for agriculture, the total waste collection rate (flow 10) is estimated based on variables from the SPOT model. BPW2 uses the estimate of collected and delivered municipal solid waste (MSW) (variable P7 in the SPOT model) divided by MSW generation (variable P1 in the SPOT model).

$$Flow10 = \frac{P7_{SPOT}}{P1_{SPOT}}$$

For the agricultural sector, BPW2 used collection rates for pesticide packaging by region from Gilbert, Ricci and Thompson, 2021, as a proxy for all agricultural plastic collection.[31] We assigned each region a BPW2 archetype (Table 4-19).

Uncollected waste (flow 11) is the complement of the total waste collection rate (flow 10) and is calculated in Pathways as 1 minus the total waste collection rate.

$$Flow11 = 1 - Flow10$$

Table 4-19. Agricultural Plastic Collection Rates

Region	BPW2 archetype	Collection rates for pesticide packaging
Africa	LI	21%
Asia	LMI	3%
Australia, Canada, U.S., New Zealand	HI	40%
Europe	HI	61%
South America	UMI	58%

Source: Jane Gilbert, Marco Ricci, and Richard H. Thompson, *Assessment of Agricultural Plastics and Their Sustainability: A Call for Action*, 2021

BPW2 estimated informal (flow 13) and formal (flow 12) collection rates and formal direct collection for sorting (flow 14) rates using the following variables from the SPOT model:

- P1: Total MSW generated
- P7: Collected and delivered MSW
- C0: Plastic in MSW as % of MSW generation
- P14a: Informal collection of plastic for dry recycling

We calculated the rate of informal collection by dividing the SPOT estimate of informal collection of plastic for dry recycling by the amount of plastic MSW collected. In the model, the mass growth of this flow is capped at the projected population growth rate of each income archetype. Flow 12 (formal collection) is the complement to this rate. Collection rates are applied the same across all plastic types and only varies by archetype.

$$Collected\ MSW_{plastic} = P7_{SPOT} \times C0_{SPOT}$$

$$Flow13 = \frac{P14a_{SPOT}}{Collected\ MSW_{plastic}}$$

$$Flow12 = 1 - Flow13$$

BPW2 also calculated formal collection for sorting (flow 14) for non-HI archetypes using the SPOT estimate of formal collection of plastic for dry recycling and dividing that by the total amount of formally collected plastic MSW. The amount of plastic collected in "mixed collection" (flow 15) is the complement of flow 14.

$$Formally\ Collected\ MSW_{plastic} = Collected\ MSW_{plastic} \times Flow12$$

$$Flow14 = \frac{P15a_{SPOT}}{Formally\ Collected\ MSW_{plastic}}$$

$$Flow15 = 1 - Flow14$$

For the HI archetypes, BPW2 used different rates for plastic collected specifically for recycling from various countries, including the United States, United Kingdom, European Union and Australia.[32] The values gathered for collection for recycling were averaged together, yielding the following rates in Table 4-20. As previously stated, flow 15 is the complement of flow 14.

Table 4-20. Collection for Recycling Rates for Packaging in the HI Archetypes

Product	Share of mass collected that is collected for recycling
Bottles	47.9%
Other rigid packaging	26.8%
Flexible packaging	11.1%
Multilayer/material packaging	0.0%

As in BPW1, BPW2 assumed that no plastic is collected for recycling from mixed collection (flow 16). Therefore, all mixed collection waste goes to "unsorted waste" (flow 17).

$$Flow16 = 0$$

$$Flow17 = 1 - Flow16$$

4.E.2. Waste exports and imports

BPW2 estimated waste exports with data from the U.N. trade data.[33] The primary export flow (flow 20) is an absolute flow in Pathways (meaning the input value to the model is in metric tons per year). BPW2 only captured the amount of plastic waste traded between archetypes – we did not estimate the waste trade of substitute materials.

We used 2021 data from the following three U.N. Commodity Trade Statistics Database (U.N. Comtrade) material codes to estimate total plastic waste trade:

- Waste, parings and scrap, of plastic (Code 3915)
- Paper or paperboard; waste and scrap of paper or paperboard n.e.c. in heading no. 4707 and of unsorted waste and scrap (Code 470790)
- Textiles, worn clothing and other worn articles (Code 6309)

BPW2 attempted to capture both legal plastic waste trade and embedded/illegal plastic waste trade in other reported waste types by adding together the total reported plastic waste traded between countries with a portion of the mass of paper waste traded. According to Karlsson et al., 2023, 5% of paper waste bales could be plastic.[34] We assumed that the total amount of plastic waste traded between countries has the same split between plastic types as the original country-level use shares (split across all plastic types). We also assumed that the growth in the mass of plastic waste traded between countries increases at the same rate as plastic use over the period of the model.

For textiles, we captured the amount of synthetic second-hand clothes traded between archetypes by multiplying the mass of worn clothes traded by the average share of textiles that are synthetic (67%).[35] This mass of second-hand clothes traded is added to the initial estimate of textile plastic scrap traded (described above). This mass is important to include because recent reports have found that approximately 40% of textile waste exported to Africa is sent to dumpsites or open burning, so the trade of second-hand clothes is essentially an additional type of waste trade.[36]

BPW2 also improved on the initial estimate of exported waste from BPW1 through new capabilities in the Pathways model that allows the user to specify how much of the exported waste is sent to other archetypes (flows 56 through 59). We achieved this by aggregating the U.N. Comtrade Plastic scraps export data (Code 3915) to the archetype level for exports and the destination of the exports. We then calculated the share of mass exported from one archetype that goes to each archetype. Flows 56 through 59 remain constant over the modelling period. This assumes that trade patterns will remain constant over the modelling period. The model allows for trading within archetypes (the HI-R archetype can export to the HI-U archetype); however, it assumes that all exported waste is sent to urban archetypes. This is defined in the "transport" tab of the model input sheets.

Plastic waste imports (flow 23) are calculated in Pathways based on the sum of exports from other archetypes that are sent to the specific archetype the model is calculating. Once waste is imported, it follows all the same flows as the archetype it was imported to after the Sorting box.

4.E.3. Waste sorting

Waste sorting refers to the process of selecting the most recyclable materials from collected waste and preparing it for recycling. BPW2 accounted for sorting by the informal sector and the formal sector. It also details the pathways for waste that have been rejected during the sorting process.

a) Informal sorting

For informally collected waste, BPW2 estimated the amount of collected material rejected during sorting (flow 19) using the following variables from the SPOT model:

- P14aa: Informal collection of rigid plastic for dry recycling
- P14ab: Informal collection of flexible plastic for dry recycling
- P22aa: Informal sector rigid plastic rejects from dry recycling
- P22ab: Informal sector flexible plastic rejects from dry recycling

The format (rigid versus flexible) of a plastic product is key for determining the recyclability of a plastic product. Therefore, the rejection rate used in BPW2 for informal sorting varies by product format. All plastic types were assigned a format, even if they do not have explicit product breakdowns, like the ones that exist for packaging and consumer and institutional products (see

Table 3-3). These rejection rates were calculated using the SPOT data mentioned above and the following equations:

$$Flow19_{rigid} = \frac{P22aa_{SPOT}}{P14aa_{SPOT}}$$

$$Flow19_{flex} = \frac{P22ab_{SPOT}}{P14ab_{SPOT}}$$

The amount of informally collected plastic that is sent to recycling (flow 18) is the complement of flow 19. Because flow 19 varies by format, flow 18 also varies by format.

$$Flow18_{rigid} = 1 - Flow19_{rigid}$$

b) Formal sorting

Losses from formal sorting (flow 21) were estimated using a variety of sources and expert opinion. [37] These loss rates vary by archetype, sector and polymer (but do not vary by product). BPW2 calculated sorting loss rates by separating estimates of total sorting and reprocessing losses into losses from sorting and losses from reprocessing. These losses from reprocessing cover both the closed-loop and open-loop mechanical recycling losses (flows 33 and 34) in the Recycling Module.

OECD's ENV-Linkages model uses total loss rates for sorting and reprocessing by polymer, sector and OECD region. We separated these losses into losses during sorting and losses during recycling using estimates from the expert panel on the probability of a polymer being rejected during the sorting process, Chruszcz and Reeve, 2018, which provided the composition of MSW by polymer, and Roosen et al., 2020, which provides total loss rates by polymer for sorting and reprocessing. [38] The probability of a polymer being rejected during sorting was combined with the average composition of the polymer in kerbside waste. We divided this value by the total amount of losses during sorting and recycling to get the share of losses that occur during sorting for a specific polymer. The remainder is the share of losses that occur during recycling for a specific polymer.

Using those fractions, we calculated the loss rate during sorting by sector, archetype and polymer using a representative "mass" of 100 kilotons (kt). We multiplied the loss rates for the OECD ENV-Linkages model (which vary by OECD region, sector and polymer) by the portion of losses that occur during sorting by polymer. For example, if the aggregate loss rate is 20% for a specific sector, polymer and OECD region (meaning 20% of plastic waste that is collected for recycling is lost), then total losses are 20 kt if 100 kt is collected for recycling. If 17% of losses happen during sorting for that specific polymer, (0.17 * 20) = 3.4 kt is lost during sorting. Therefore, 3.4 kt / 100 kt = 3.4% sorting loss rate for the OECD region, sector and polymer. The tables in the Collection and Sorting Flows Tables section show the resulting loss rates from these calculations.

We then calculated the losses from recycling using the remaining mass. If 3.4 kt are lost during sorting, then 16.6 kt need to be lost during reprocessing to achieve the aggregate 20% loss rate. By subtracting 3.4 kt from 100 kt, we get the remaining mass flowing through to reprocessing (96.6 kt). If we then divide 16.6 kt by the remainder, we get the loss rate during reprocessing. For this example, the recycling loss rate is 17.2%.

We converted the OECD regions to the BPW2 archetypes by cross walking the regions to countries and aggregating to the archetype level by taking the average loss rates across the countries in the archetypes. We assume the same loss rate will be applied for open-loop and closed-loop recycling, as was done in BPW1. Additionally, plastic sectors not included in the OECD loss rate data (agriculture, aquaculture and fisheries) are all assigned the "other" application polymer loss rates.

c) Pathways for unsorted waste

All sorted waste in the Waste Collection and Sorting Module that is not sent for recycling (waste in mixed collection, rejects from informal sorting, and rejects from formal sorting) ends up in the "unsorted waste" box. We calculated the share of this waste that is mismanaged (flow 24) using the following variables from the SPOT model:

- P7: Collected and delivered MSW
- P10: Uncontrolled disposal of MSW
- P12i: Other treatment of MSW
- P13: Collected MSW for dry recycling

The variable P10 represents the amount of collected waste that is mismanaged and subtracting the variables P12i and P13 from P7 yields a value that represents the amount of mass available to either be sent for managed disposal (engineered landfills and incineration) or to be mismanaged. We used the equation below to estimate flow 24. The amount of waste sent for managed disposal (flow 25) is the complement of flow 24. These flows are the same for all plastic types.

$$Flow24 = \frac{P10_{SPOT}}{(P7_{SPOT} - P12i_{SPOT} - P13_{SPOT})}$$

$$Flow25 = 1 - Flow24$$

4.E.4. Substitute waste collection and sorting

For substitute materials, BPW2 calculated collection and sorting flows using many of the same variables from the SPOT model as the plastic material types. The total collection rates are the same by archetype. The amount of substitute waste collected by informal collection is estimated from the SPOT model as the amount of informal collection of MSW for dry recycling (variable P14) divided by the amount of collected and delivered MSW (variable P7).

In BPW2, we assumed that all substitute waste goes into mixed collection (flow 15) and flow 16, the amount of waste collected from mixed recycling for sorting, is calculated as the amount of collected of MSW for dry recycling (variable P13) divided by the amount of collected and delivered MSW (variable P7). We assumed there are no losses from formal sorting for substitute waste and that all informally collected substitute waste goes to recycling (no informal sorting losses).

4.E.5. Collection and sorting flows tables

The following tables show the actual flows used for BPW2 in the Pathways model for the Waste Collection and Sorting Module. Results from the model may be different due to constraints placed on certain boxes and flows in various scenarios.

Table 4-21. Formal Collection Rates for Packaging Sector Plastic Waste in 2025

Percentage of plastic packaging waste that gets formally collected, or the input for flow 12 in the model

	Percentage of plastic packaging waste that is formally collected, by archetype							
Format	**HI-U**	**HI-R**	**UMI-U**	**UMI-R**	**LMI-U**	**LMI-R**	**LI-U**	**LI-R**
Rigid	99.9%	99.9%	67.2%	74.4%	47.0%	46.7%	35.9%	29.4%
Flexible	99.9%	99.9%	76.9%	82.2%	66.7%	67.1%	60.4%	58.0%

Table 4-22. Formal Sorting Rates for Packaging Sector Plastic Waste

Percentage of plastic packaging waste that gets formally collected and sent to recycling, by plastic type and archetype, calculated as the sum of flow 22 divided by the sum of flows 14 and 23

			Percentage of formally collected plastic packaging waste that is sent to recycling, by archetype							
Format	**Polymer**	**Product**	**HI-U**	**HI-R**	**UMI-U**	**UMI-R**	**LMI-U**	**LMI-R**	**LI-U**	**LI-R**
Rigid	Other	Rigid non-food packaging	0.8%	0.9%	0.2%	0.0%	0.5%	0.0%	0.6%	0.0%
Rigid	Other	Rigid food packaging	0.8%	0.9%	0.2%	0.0%	0.5%	0.0%	0.6%	0.0%
Rigid	LDPE/LLDPE	Rigid non-food packaging	16.8%	17.3%	5.3%	0.2%	7.7%	0.2%	4.9%	0.0%
Rigid	LDPE/LLDPE	Rigid food packaging	16.8%	17.3%	5.3%	0.2%	7.7%	0.2%	4.9%	0.0%
Rigid	LDPE/LLDPE	Other bottles	18.1%	18.5%	5.3%	0.2%	7.7%	0.2%	4.9%	0.0%
Rigid	HDPE	Rigid non-food packaging	81.4%	84.0%	25.2%	1.0%	35.2%	1.0%	25.5%	0.0%
Rigid	HDPE	Rigid food packaging	81.4%	84.0%	25.2%	1.0%	35.2%	1.0%	25.5%	0.0%
Rigid	HDPE	Other bottles	88.4%	90.3%	25.2%	1.0%	35.2%	1.0%	25.5%	0.0%
Rigid	HDPE	PET bottles	88.4%	90.3%	25.2%	1.0%	35.2%	1.0%	25.5%	0.0%
Rigid	PP	Rigid non-food packaging	49.3%	50.8%	17.5%	0.9%	30.9%	1.0%	20.6%	0.0%
Rigid	PP	Rigid food packaging	49.3%	50.8%	17.5%	0.9%	30.9%	1.0%	20.6%	0.0%
Rigid	PP	Other bottles	53.2%	54.3%	17.5%	0.9%	30.9%	1.0%	20.6%	0.0%
Rigid	PP	PET bottles	53.2%	54.3%	17.5%	0.9%	30.9%	1.0%	20.6%	0.0%

Format	Polymer	Product	Percentage of formally collected plastic packaging waste that is sent to recycling, by archetype							
			HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Rigid	PS/EPS	Rigid non-food packaging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rigid	PS/EPS	Rigid food packaging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rigid	PVC	Rigid non-food packaging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rigid	PVC	Rigid food packaging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rigid	PVC	Other bottles	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rigid	PET	Other bottles	87.4%	89.2%	18.1%	0.9%	34.9%	1.0%	30.6%	0.0%
Rigid	PET	Rigid food packaging	81.3%	83.9%	18.1%	0.9%	34.9%	1.0%	30.6%	0.0%
Rigid	PET	Rigid non-food packaging	81.3%	83.9%	18.1%	0.9%	34.9%	1.0%	30.6%	0.0%
Rigid	PET	PET bottles	87.4%	89.2%	18.1%	0.9%	34.9%	1.0%	30.6%	0.0%
Flexible	Other	Flexible packaging	0.7%	0.7%	0.2%	0.0%	0.5%	0.0%	0.6%	0.0%
Flexible	Other	Multilayer packaging	0.0%	0.0%	0.2%	0.0%	0.5%	0.0%	0.6%	0.0%
Flexible	LDPE/LLDPE	Flexible packaging	13.1%	13.3%	5.2%	0.2%	7.7%	0.2%	5.2%	0.0%
Flexible	LDPE/LLDPE	Multilayer packaging	0.1%	0.0%	5.2%	0.2%	7.7%	0.2%	5.2%	0.0%
Flexible	HDPE	Flexible packaging	12.9%	13.0%	5.5%	0.2%	7.7%	0.2%	5.7%	0.0%
Flexible	PP	Flexible packaging	13.4%	13.6%	4.1%	0.2%	7.1%	0.2%	5.0%	0.0%
Flexible	PP	Multilayer packaging	0.1%	0.0%	4.1%	0.2%	7.1%	0.2%	5.0%	0.0%
Flexible	PS/EPS	Flexible packaging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Flexible	PVC	Flexible packaging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Flexible	PVC	Multilayer packaging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Flexible	PET	Flexible packaging	13.6%	13.9%	4.1%	0.2%	8.0%	0.2%	7.2%	0.0%
Flexible	PET	Multilayer packaging	0.1%	0.0%	4.1%	0.2%	8.0%	0.2%	7.2%	0.0%
Rigid	AVERAGE		69.6%	72.1%	19.0%	0.9%	30.7%	0.9%	23.0%	0.0%
Flexible	AVERAGE		12.5%	12.8%	4.7%	0.2%	7.1%	0.2%	4.9%	0.0%

Table 4-23. Informal Collection Rates for Packaging Sector Plastic Waste

Percentage of plastic packaging waste that gets informally collected, by archetype, calculated as the sum of flows 18 and 19 divided by flow 9

Format	Polymer	Product	Percentage of plastic packaging waste that is informally collected, by archetype							
			HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Rigid	Other	Rigid non-food packaging	0.0%	0.0%	25.3%	13.3%	39.4%	20.4%	27.4%	16.1%
Rigid	Other	Rigid food packaging	0.0%	0.0%	25.3%	13.3%	39.4%	20.4%	27.4%	16.1%
Rigid	LDPE/LLDPE	Rigid non-food packaging	0.0%	0.0%	25.2%	13.3%	38.8%	20.4%	27.6%	16.1%
Rigid	LDPE/LLDPE	Rigid food packaging	0.0%	0.0%	25.2%	13.3%	38.8%	20.4%	27.6%	16.1%
Rigid	LDPE/LLDPE	Other bottles	0.0%	0.0%	25.2%	13.3%	38.8%	20.4%	27.6%	16.1%
Rigid	HDPE	Rigid non-food packaging	0.0%	0.0%	25.3%	13.3%	38.8%	20.4%	27.7%	16.1%
Rigid	HDPE	Rigid food packaging	0.0%	0.0%	25.3%	13.3%	38.8%	20.4%	27.7%	16.1%
Rigid	HDPE	Other bottles	0.0%	0.0%	25.3%	13.3%	38.8%	20.4%	27.7%	16.1%
Rigid	HDPE	PET bottles	0.0%	0.0%	25.3%	13.3%	38.8%	20.4%	27.7%	16.1%
Rigid	PP	Rigid non-food packaging	0.0%	0.0%	25.2%	13.3%	38.3%	20.4%	27.9%	16.1%
Rigid	PP	Rigid food packaging	0.0%	0.0%	25.2%	13.3%	38.3%	20.4%	27.9%	16.1%
Rigid	PP	Other bottles	0.0%	0.0%	25.2%	13.3%	38.3%	20.4%	27.9%	16.1%
Rigid	PP	PET bottles	0.0%	0.0%	25.2%	13.3%	38.3%	20.4%	27.9%	16.1%
Rigid	PS/EPS	Rigid non-food packaging	0.0%	0.0%	25.3%	13.3%	38.4%	20.4%	27.1%	16.1%
Rigid	PS/EPS	Rigid food packaging	0.0%	0.0%	25.3%	13.3%	38.4%	20.4%	27.1%	16.1%
Rigid	PVC	Rigid non-food packaging	0.0%	0.0%	25.3%	13.3%	38.4%	20.4%	27.3%	16.1%
Rigid	PVC	Rigid food packaging	0.0%	0.0%	25.3%	13.3%	38.4%	20.4%	27.3%	16.1%
Rigid	PVC	Other bottles	0.0%	0.0%	25.3%	13.3%	38.4%	20.4%	27.3%	16.1%
Rigid	PET	Other bottles	0.0%	0.0%	25.3%	13.3%	38.2%	20.4%	28.2%	16.1%
Rigid	PET	Rigid food packaging	0.0%	0.0%	25.3%	13.3%	38.2%	20.4%	28.2%	16.1%
Rigid	PET	Rigid non-food packaging	0.0%	0.0%	25.3%	13.3%	38.2%	20.4%	28.2%	16.1%
Rigid	PET	PET bottles	0.0%	0.0%	25.3%	13.3%	38.2%	20.4%	28.2%	16.1%
Flexible	Other	Flexible packaging	0.0%	0.0%	25.3%	13.3%	41.2%	20.4%	27.0%	16.1%
Flexible	Other	Multilayer packaging	0.0%	0.0%	25.3%	13.3%	41.2%	20.4%	27.0%	16.1%

Format	Polymer	Product	Percentage of plastic packaging waste that is informally collected, by archetype							
			HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Flexible	LDPE/LLDPE	Flexible packaging	0.0%	0.0%	25.2%	13.3%	40.4%	20.4%	25.8%	16.1%
Flexible	LDPE/LLDPE	Multilayer packaging	0.0%	0.0%	25.2%	13.3%	40.4%	20.4%	25.8%	16.1%
Flexible	HDPE	Flexible packaging	0.0%	0.0%	25.3%	13.3%	40.7%	20.4%	25.9%	16.1%
Flexible	PP	Flexible packaging	0.0%	0.0%	25.2%	13.3%	39.2%	20.4%	25.6%	16.1%
Flexible	PP	Multilayer packaging	0.0%	0.0%	25.2%	13.3%	39.2%	20.4%	25.6%	16.1%
Flexible	PS/EPS	Flexible packaging	0.0%	0.0%	25.3%	13.3%	38.8%	20.4%	25.6%	16.1%
Flexible	PVC	Flexible packaging	0.0%	0.0%	25.3%	13.3%	39.5%	20.4%	25.6%	16.1%
Flexible	PVC	Multilayer packaging	0.0%	0.0%	25.3%	13.3%	39.5%	20.4%	25.6%	16.1%
Flexible	PET	Flexible packaging	0.0%	0.0%	25.3%	13.3%	38.3%	20.4%	25.9%	16.1%
Flexible	PET	Multilayer packaging	0.0%	0.0%	25.3%	13.3%	38.3%	20.4%	25.9%	16.1%

Table 4-24. Informal Sorting Rates for Packaging Sector Plastic Waste

Percentage of informally collected plastic packaging waste that gets sent to recycling, by archetype.

Format	Polymer	Product	Percentage of informally collected plastic packaging waste that is sent to recycling, by archetype							
			HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Rigid	Other	Rigid non-food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	0.0%	0.0%
Rigid	Other	Rigid food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	0.0%	0.0%
Rigid	LDPE/LLDPE	Rigid non-food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	LDPE/LLDPE	Rigid food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	LDPE/LLDPE	Other bottles	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	HDPE	Rigid non-food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	HDPE	Rigid food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	HDPE	Other bottles	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%

Format	Polymer	Product	Percentage of informally collected plastic packaging waste that is sent to recycling, by archetype							
			HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Rigid	HDPE	PET bottles	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PP	Rigid non-food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PP	Rigid food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PP	Other bottles	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PP	PET bottles	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PS/EPS	Rigid non-food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PS/EPS	Rigid food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PVC	Rigid non-food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PVC	Rigid food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PVC	Other bottles	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PET	Other bottles	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PET	Rigid food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PET	Rigid non-food packaging	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Rigid	PET	PET bottles	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Flexible	Other	Flexible packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	0.0%	0.0%
Flexible	Other	Multilayer packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	0.0%	0.0%
Flexible	LDPE/LLDPE	Flexible packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%
Flexible	LDPE/LLDPE	Multilayer packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%
Flexible	HDPE	Flexible packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%

Format	Polymer	Product	Percentage of informally collected plastic packaging waste that is sent to recycling, by archetype							
			HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Flexible	PP	Flexible packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%
Flexible	PP	Multilayer packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%
Flexible	PS/EPS	Flexible packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%
Flexible	PVC	Flexible packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%
Flexible	PVC	Multilayer packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%
Flexible	PET	Flexible packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%
Flexible	PET	Multilayer packaging	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%
Rigid	AVERAGE		85.1%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%	81.2%
Flexible	AVERAGE		81.2%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%	85.1%

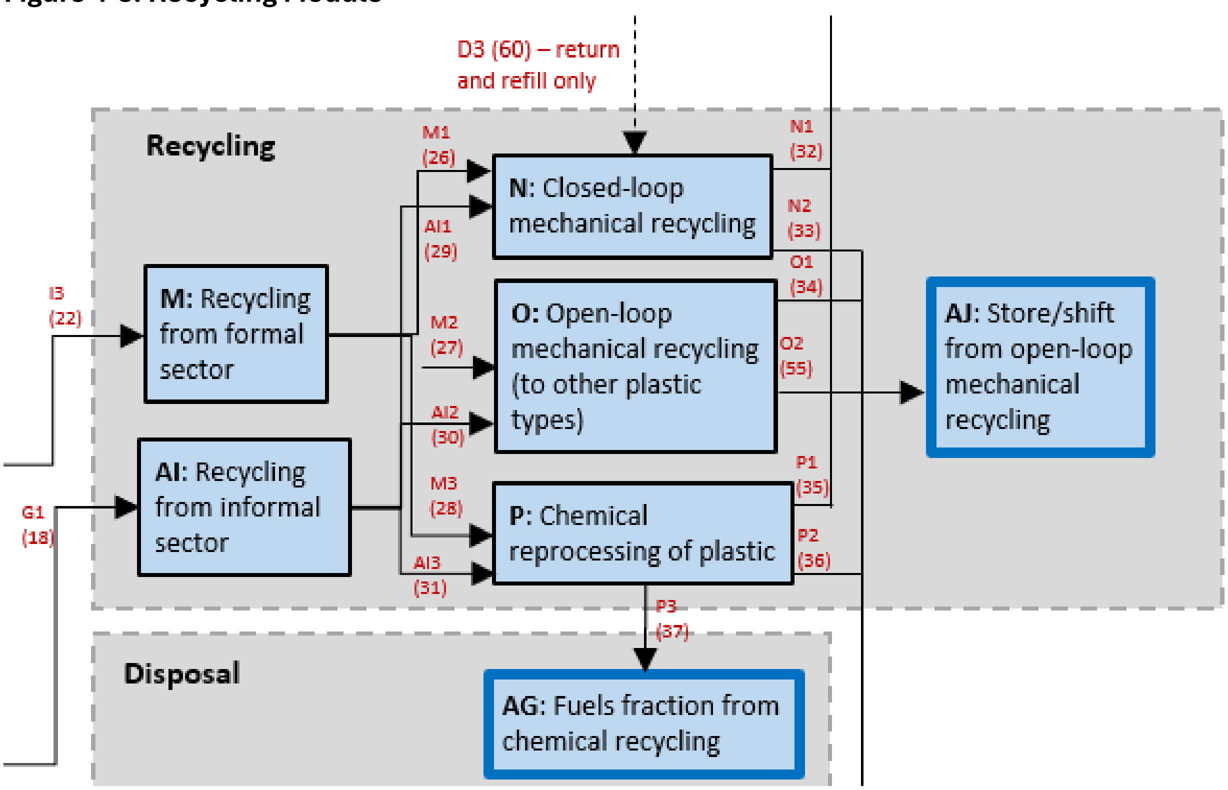
Note: The remaining percentage gets sent to “unsorted waste” (box J). Flow 18 (amount of informally collected plastic sent to recycling) divided by flow 18 + 19 (total amount of plastic collected informally)

4.F. Recycling Module

Figure 4-3 shows the flows in the Recycling Module for BPW2. This module calculates the material mass flowing through three distinct recycling processes: closed-loop mechanical recycling, open-loop mechanical recycling and chemical reprocessing. Chemical reprocessing is further disaggregated into two different processes: plastic-to-fuel (P2F) and plastic-to-plastic (P2P), also called chemical recycling. Chemical reprocessing is only relevant for plastic materials and does not apply to substitute non-plastic materials. P2F chemical reprocessing (flow 37) is presented as an end-of-life stage in the BPW2 model because the resulting fuel leaves the waste system map. Because P2F does not affect plastic production and use, our analysis treats it as a form of disposal. P2P chemical reprocessing (flow 35) produces plastic materials that are used to displace virgin plastic production (flow 54) at the polymerization phase.

Closed-loop mechanical recycling is represented by flow 32 and is mass that will replace virgin production (flow 54) within the same plastic category (i.e., a PET bottle recycled into another PET bottle) in the product conversion phase in the model outputs. Open-loop mechanical recycling is represented by flow 55 and the mass does not replace virgin production (flow 54). At this time, our model does not explicitly account for the relationship between plastic categories (e.g., PET bottles being repurposed into textiles) that would be relevant for open-loop mechanical recycling.

Figure 4-3. Recycling Module



4.F.1. Share of mass to each type of recycling

BPW2 estimated the share of formally and informally sorted mass that is sent to each recycling type using data and assumptions from BPW1. The values varied by plastic type format in BPW1 (rigid, flexible and multilayer) and were cross-walked to the BPW2 plastic types using the assigned formats.

For chemical recycling, the share of plastic that is reprocessed by P2F or P2P uses the same assumptions as BPW1. Refer to the technical appendix of BPW1 for more details.

4.F.2. Losses during recycling

For losses during mechanical recycling, see the methods discussed in the Formal Sorting section.

4.F.3. Substitute materials recycling

For substitute materials, BPW2 assumed that all glass and metal go to closed-loop recycling and that all paper and compostables go to open-loop recycling. We also assume there are no losses from closed-loop or open-loop recycling. All return and refill materials go to closed-loop recycling and the plastic return and refill material types are assumed to have the same closed-loop recycling loss rate as rigid HDPE bottles.

4.F.4. Recycling flows tables

The following tables show the actual flows used for BPW2 in the Pathways model for the Recycling Module.

Table 4-25. Formal Sorting to Closed-Loop Recycling Rates

Percentage of formally sorted plastic packaging waste that is sent to closed-loop recycling, by archetype and format, for flow 26

	Percentage of formally sorted packaging waste sent to closed-loop recycling							
Format	**HI-U**	**HI-R**	**UMI-U**	**UMI-R**	**LMI-U**	**LMI-R**	**LI-U**	**LI-R**
Rigid	65.7%	65.7%	12.5%	12.5%	6.3%	6.3%	0.0%	0.0%
Flexible	12.3%	12.5%	6.1%	6.3%	2.9%	3.1%	0.0%	0.0%

Table 4-26. Formal Sorting to Open-Loop Recycling Rates

Percentage of formally sorted plastic packaging waste that is sent to open-loop recycling, by archetype, calculated as 100% minus flow 26 minus flow 28

	Percentage of formally sorted packaging waste sent to open-loop recycling							
Format	**HI-U**	**HI-R**	**UMI-U**	**UMI-R**	**LMI-U**	**LMI-R**	**LI-U**	**LI-R**
Rigid	34.3%	34.3%	87.5%	87.5%	93.8%	93.8%	100.0%	100.0%
Flexible	86.0%	87.5%	91.8%	93.8%	91.2%	96.9%	100.0%	100.0%

Table 4-27. Formal Sorting to Chemical Recycling Rates

Percentage of formally sorted plastic packaging waste that is sent to chemical recycling, by archetype

Format	Percentage of formally sorted packaging waste sent to chemical recycling							
	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Rigid	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Flexible	1.8%	0.0%	2.1%	0.0%	5.8%	0.0%	0.0%	0.0%

Table 4-28. Informal Sorting to Closed-Loop Recycling Rates

Percentage of informally sorted plastic packaging waste that is sent to closed-loop recycling, by archetype

Format	Percentage of informally sorted packaging waste sent to closed-loop recycling							
	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Rigid	73.7%	73.7%	26.3%	26.3%	26.3%	26.3%	26.3%	26.3%
Flexible	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%

Table 4-29. Informal Sorting to Open-Loop Recycling Rates

Percentage of informally sorted plastic packaging waste that is sent to open-loop recycling, by archetype

Format	Percentage of informally sorted packaging waste sent to open-loop recycling							
	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Rigid	26.3%	26.3%	73.7%	73.7%	73.7%	73.7%	73.7%	73.7%
Flexible	94.7%	94.7%	94.7%	94.7%	94.7%	94.7%	94.7%	94.7%

Table 4-30. Informal Sorting to Chemical Reprocessing Rates

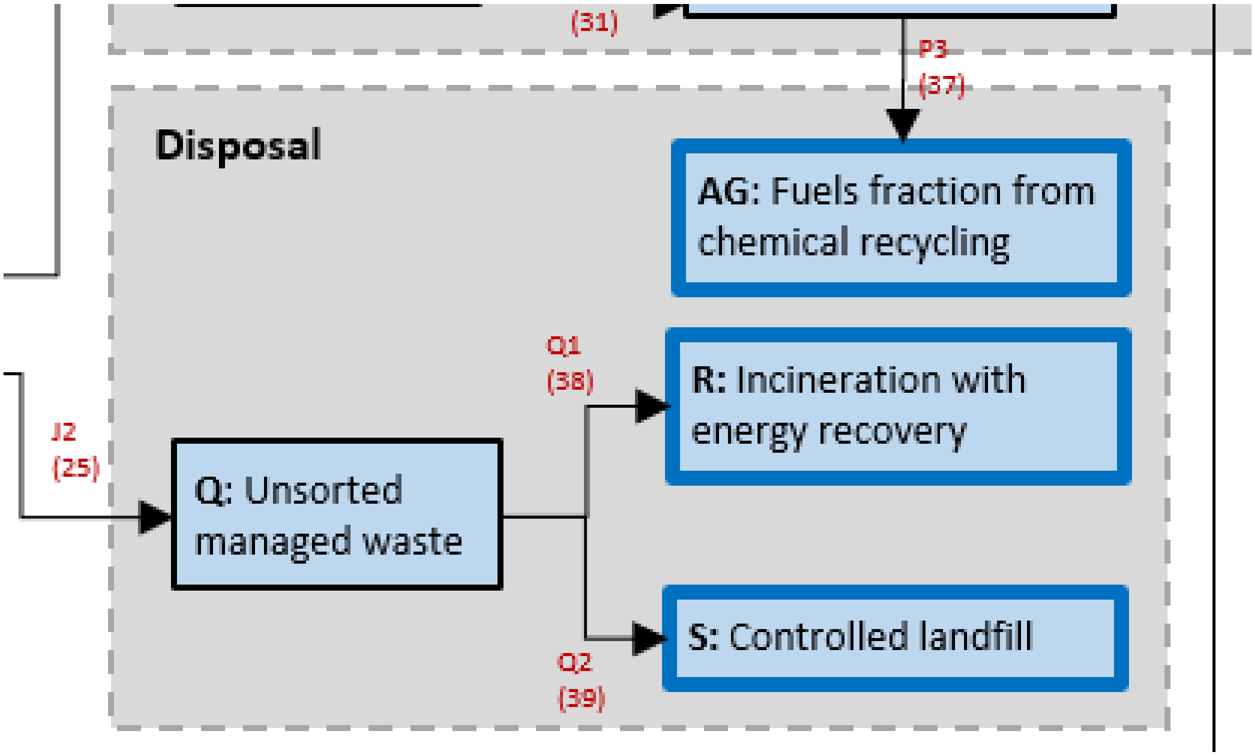
Percentage of formally sorted plastic packaging waste that is sent to chemical reprocessing, by archetype

Format	Percentage of informally sorted packaging waste sent to chemical recycling							
	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Rigid	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Flexible	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

4.G. Disposal Module

Figure 4-4 shows the Disposal Module in BPW2. This module estimates the amount of managed waste that is sent to landfills or is incinerated with energy recovery. As in BPW1, dumpsites or unmanaged landfills are not included in the Disposal Module because they are considered mismanaged waste. Incineration without energy recovery has also been excluded because these types of plants make up an insignificant share of plastic waste treated at the global level.[39] BPW2 assumes that all plastic types and substitute material types have the same value for these flows and only varies by archetype. This assumption was determined from careful discussion with the expert panel.

Figure 4-4. Disposal Module



BPW2 estimated the share of managed waste that is incinerated with energy recovery (flow 38) or disposed of in engineered landfills (flow 39) using the following variables from the SPOT model:

- P11: Controlled disposal of MSW
- P12ii: Incineration

$$Flow38 = \frac{P12ii_{SPOT}}{(P12ii_{SPOT} + P11_{SPOT})}$$

$$Flow39 = 1 - Flow38$$

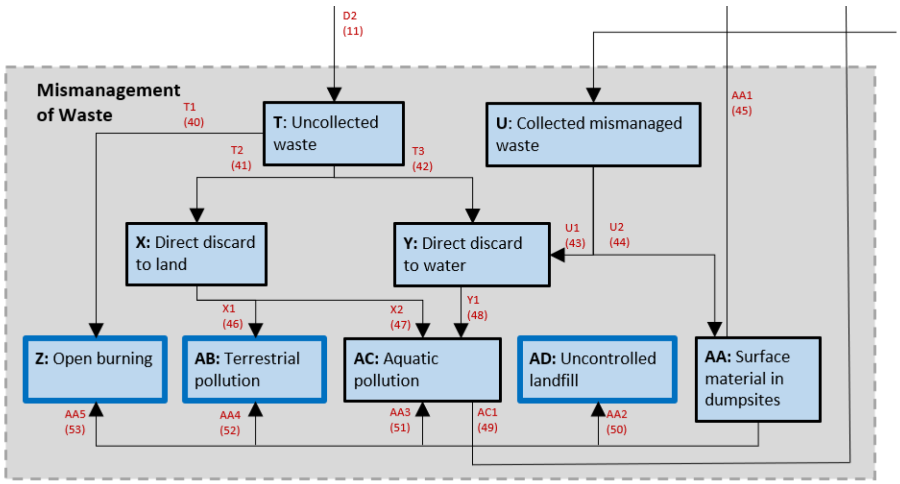
We aligned the SPOT model with the BPW2 system map by excluding their variable "other treatment of MSW" to only capture the split between incineration and landfilling. This excluded variable primarily captures the amount of MSW composted.

P2F is also considered a form of disposal in our analysis, as noted earlier.

4.H. Mismanagement of Waste Module

Figure 4-5 shows the flows in the Mismanagement of Waste Module. We define mismanaged waste as waste that has been released or deposited in a place from where it can move into the natural environment (intentionally or otherwise). Mass enters this box from two flows – uncollected waste and mismanaged collected waste. This mass then flows by various pathways to either be open burned, stored in a dumpsite, or enter the environment as terrestrial or aquatic pollution. The definitions of these boxes and flows are the same as in BPW1. As in BPW1, this module also accounts for two pathways of collection from mismanaged sources: dumpsite recovery (flow 45) and collection for aquatic environments (flow 49).

Figure 4-5. Mismanagement of Waste Module



4.H.1. Mismanaged waste pathways

BPW2 used much of the data from BPW1 related to mismanagement of waste for this module. However, BPW2 used updated data on the rates of open burning from the SPOT model (flows 40 and 55). Flow 40 is calculated from the SPOT variable "uncollected MSW openly burned" (C10) and flow 53 is calculated from the SPOT variable "open burning of uncontrolled disposal" (C8). These variables in the SPOT model are represented as fractions of waste at the municipal level. We aggregated them to the archetype level by taking the population-weighted average of the shares. The resulting flows only vary by archetype.

We pulled data from BPW1 for the flows that correspond to the BPW2 flows 41 through 52 (Table 4-31). We scaled flows 41 and 42 so they make up the remaining percentage of the total mass in box T after the new open burning rates (flow 40) are assigned, but so they maintain the same ratio to each other as they had in BPW1. We used the same approach for flows 45, 50, 51 and 52 with the new values for flow 53 derived from the SPOT model. These flows vary both by archetype and format.

For the agricultural sector, we assumed that there is no direct discard to water, so flow 42 is set to zero.

Table 4-31. BPW1 to BPW2 Flow Crosswalk

BPW1 description	BPW1 flow	BPW2 flow
Total informal household and street collection	Arrow B2	E2
Share of formal collected for recycling (separated at source)	Arrow C1	F1
Mass of mixed waste to chemical conversion (as % of box C)	Arrow E1	M3
Share of mixed waste to dirty materials recovery facility	Arrow E3	H1

Share of informal sector to closed-loop	Arrow D1	AI1
Share of informal sector to open-loop	Arrow D2	AI2
Share of informal sector to chemical conversion	Arrow D3	AI3
Share of informal sector to losses	Arrow D4	G2
Share sorted waste to closed-loop	Arrow F1	M1
Share sorted waste to open-loop	Arrow F2	M2
Share sorted waste to losses	Arrow F3	I2
Total exported waste	Arrow F4/box G	I1
Total imported waste	Arrow H1/box H	L1
Share of closed-loop actually recycled	Arrow I1	N1
Share of closed-loop to losses	Arrow I2	N2
Share of open-loop actually recycled	Arrow J0	O2
Share of open-loop to losses	Arrow J1	O1
Share of chemical to plastic	Arrow K1	P1
Share of chemical to fuel	Arrow K2	P3
Share of chemical to losses	Arrow K3	P2
% managed waste from post-collection waste	Arrow L1	J2
Share of managed to thermal treatment	Arrow M1/box O	Q1
Share of managed to engineered landfills	Arrow M2/box N	Q2
Share uncollected to open burn	Arrow Q1	T1
Share uncollected to terrestrial dumping (zone A)	Arrow Q2 (zone A)	T2
Share uncollected to terrestrial dumping (zone B)	Arrow Q2 (zone B)	T2
Share uncollected to terrestrial dumping (zone C)	Arrow Q2 (zone C)	T2
Share uncollected discarded direct to water (zone A)	Arrow Q3 (zone A)	T3
Share uncollected discarded direct to water (zone B)	Arrow Q3 (zone B)	T3
Share uncollected discarded direct to water (zone C)	Arrow Q3 (zone C)	T3
Share of terrestrial dumping to ocean leakage (zone A)	Arrow T1 (zone A)	X2
Share of terrestrial dumping to ocean leakage (zone B)	Arrow T1 (zone B)	X2
Share of terrestrial dumping to ocean leakage (zone C)	Arrow T1 (zone C)	X2
Share post-collection mismanaged discarded direct to water	Arrow R1	U1
Share post-collection mismanaged to dumpsite or uncontrolled landfill	Arrow R2	U2
Dumpsite recovery	Arrow V1	AA1
Share of dumpsite/uncontrolled landfill to open burn	Arrow V2	AA5
Share of dumpsite/uncontrolled landfill to ocean leakage (zone A)	Arrow V3 (zone A)	AA3
Share of dumpsite/uncontrolled landfill to ocean leakage (zone B)	Arrow V3 (zone B)	AA3
Share of dumpsite/uncontrolled landfill to ocean leakage (zone C)	Arrow V3 (zone C)	AA3
Post-leakage collection (river traps, clean-ups)	Arrow W1	AC1
Share of dumpsite/uncontrolled landfill to terrestrial leakage (zone 1)	Arrow V4 (zone 1)	AA4
Share of dumpsite/uncontrolled landfill to terrestrial leakage (zone 2)	Arrow V4 (zone 2)	AA4

4.H.2. Recovery from mismanaged sinks

BPW2 estimates the amount of mass recovered from dumpsites and aquatic environments using the outputs from the BPW1 model. In BPW1, both flows were defined as absolute flows. In BPW2, we updated these flows to be relative (percent) flows to handle the increased complexity of the model. We achieved this by dividing the resulting mass flows from BPW1 by the mass accumulated in the dumpsite and aquatic sink boxes in BPW1. This yielded the collection rates from each sink. These values vary by BPW1 material type (rigid, flexible, multimaterial). We average the collection rates for flexible and multimaterial types to create one "flexible" collection rate. We then cross-walked these format-based collection rates to the BPW2 plastic types using the format assignments listed in Table 3-3. These flows are constrained so the sum of all waste collected from these sinks is never more than the maximum total amount collected annually in BPW1. These constraints are achieved in the "flows parameters" tab of the input sheet.

4.H.3. Substitute material mismanagement

Once substitute material enters the Mismanagement of Waste Module, BPW2 does not attempt to estimate where substitute materials end up in the environment. BPW2 assumes all substitute material mass flows into the terrestrial pollution sink to achieve mass balance in the model. We report this value as the total amount of mismanaged substitute material waste. In the input sheets for the substitute materials, this means that flows 41, 44, 46 and 52 in the Mismanagement of Waste Module all have values of 1, while all other flows in this module have a value of 0.

4.I. Limitations

As with any global modelling exercise, there are data gaps and limitations associated with the BPW2 analysis. In particular, we encountered significant data limitations pertaining to plastic production outside of the packaging sector, as well as with mismanaged waste flows and recycling. Compounding these gaps is a high degree of data uncertainty, which has been addressed in the Modelling Scope section through a defined process for handling such variability. However, much of the data remains inherently uncertain, and the forthcoming MC analysis will be critical in assessing the extent to which this uncertainty influences the results.

In addition, the structure of the model does not allow for transfer of mass between plastic types. This particularly impacts the modelling of open-loop recycling where recylate is moved into a store (box AJ) rather than recirculated into product conversion (box B). As a result, that recyclate does not displace virgin plastic demand in other plastic types. For example, a PET bottle being recycled into textile fibres is not a scenario that we are able to evaluate. We recognize that this may result in an underestimate of the impact of recycling on virgin plastic production

Lastly, Pathways models microplastics in separate systems from the macroplastic modelling. While the macroplastic modelling outputs inform the microplastic modelling parameters, they do not run in parallel and, as such, the model may double-count mass in some life-cycle stages.

5. Methods for macroplastic impacts

We model three categories of impacts associated with plastic at various stages of its life cycle: (1) human health impacts, measured in disability-adjusted life years (DALYs); (2) GHG emissions, measured in carbon dioxide equivalent (CO_2e); and (3) economic impacts, including costs and jobs. For each impact category, Pathways applies our estimated unit impact (e.g., DALY) per ton of plastic at the specific points in the system map at which the impact occurs. The cumulative impacts across the system map are then summed to estimate full life-cycle impacts.

5.A. Human health impacts

To model the human health impacts of plastic at various stages of the life cycle, we employ the methods outlined in Deeney et al., 2023.[40] A DALY is a time-based measure that combines years of life lost due to premature mortality and years of life lost due to time lived in states of less than full health, or years of healthy life lost due to disability. One DALY represents the loss of the equivalent of one year of full health.[41]

Deeney et al., 2023, quantified life cycle human health impacts of plastic through a combination of material flow analysis (MFA) based on BPW1, and life-cycle assessment (LCA) conducted in Simapro 9.3.[42] The LCA used data from the Ecoinvent database 3.8 (cut-off) and followed the ReCiPe 2016 impact assessment method. As described in Deeney et al., 2023, their analysis used data from BPW1 on the mass of plastic material flows in each geographic archetype from 2016 to 2040 under BAU and various policy scenarios and paired this data with LCA to estimate human health impacts.[43]

In their supplementary material, Deeney et al., 2023, provide a detailed description of the life cycle inventory data employed in their analysis, which are based on available Ecoinvent data sets and published literature.[44] For each of the modelled polymers, including LDPE, HDPE, PP, PS, PVC and PET, the analysis aimed to match Ecoinvent data sets for impacts associated with life-cycle stages in different geographic archetypes.

The following life-cycle stages are represented in the data, with the unit values associated with the corresponding flows in Pathways when estimating human health impacts:

- Virgin polymer production (flow 54)
- Formal collection and transport to sorting plant (flows 18, 22)
- Industrial sorting (flows 14,16, 23)
- International waste trade (flows 20, 23)
- Mechanical recycling (flows 26, 27, 29, 30)
- Chemical recycling
    - Pyrolysis (flow 37)
    - Polymerization for granulate production (flow 35)
- Incineration (flow 38)
- Controlled landfill (flow 39)
- Open burning (flows 40, 53)
- Dumpsites/uncontrolled landfill (flow 50)
- Terrestrial pollution (flows 46, 52)
- Aquatic pollution (flows 47, 48, 51)

Deeney et al., 2023, provided a version of the DALY multipliers shown in the Supplementary Material that disaggregates impacts to the polymer level.[45] The DALYs per 1 million metric ton (Mt) of plastic are provided for each life-cycle stage and geographic archetype and for the total human health impacts as well as for individual impact pathways. The individual impact pathways relate environmental changes to exposure and human health impacts, and ultimately to DALYs, and include:[46]

- **Climate change**: This impact pathway relates GHG emissions to increases in GHG concentrations, increase in radiative forcing, increase in global mean temperature, and changes in disease distribution and flooding.
- **Stratospheric ozone depletion**: This impact pathway relates emissions of ozone-depleting substances (ODS), increase in tropospheric and stratospheric ODS and decrease in atmospheric ozone, increase in erythema ultraviolet B, and increase in skin cancer and cataract.
- **Ionizing radiation**: This impact pathway relates radionuclide emission and dispersion to population exposure and the resulting increase in cancer and severe hereditary effects.
- **Photochemical ozone formation**: This impact pathway relates primary and secondary aerosols, the atmospheric fate of these aerosols, human intake and mortality.
- **Fine particulate matter formation**: This impact pathway relates emissions of fine particulate matter (PM2.5) and formation of secondary PM2.5 aerosols, atmospheric fate, human intake and mortality.
- **Human carcinogenic toxicity**. This impact pathway relates chemical emissions and fate, human intake and changes in cancer incidence.
- **Human non-carcinogenic toxicity**: This impact pathway relates chemical emissions and fate, human intake, and changes in non-cancer disease incidence.
- **Water use**: This impact pathway relates water consumption to reduction in freshwater availability, water shortages for irrigation, and malnutrition and population vulnerability.

The DALY unit values are specific to each geographic archetype and reflect differences in the estimated regional electricity mixes and other Ecoinvent geography-specific data sets (e.g., proportions of open dumpsites versus uncontrolled landfills).

In preparing the data for use in the Pathways model, we map the data provided by regions in Deeney et al., 2023, to the Pathways archetypes (Table 5-1) and average the unit DALYs.[47] We assume that the DALYs per 1 Mt of plastic remain the same over the modelling period. Additionally, due to modelling limitations, we assigned a single polymer to each non-packaging, non-consumer and institutional products sector to use to estimate DALYs and GHGs.

Table 5-1. Crosswalk Between Geographies Used in Deeney et al. via Ecoinvent and Pathways Geographical Archetypes

Deeney geographies	Pathways archetype
High-income countries, Europe without Switzerland, Europe, Canada, United States, Switzerland	HI
Upper-middle-income countries, rest of world	UMI
Lower-middle-income countries, rest of world	LMI
Low-income countries, rest of world	LI

Sources: Megan Deeney et al., *Global Health Impacts of Addressing the Plastic Pollution Crisis: A Life Cycle Approach*, 2023. Ecoinvent, *Geographies*, 2023

5.B. GHG emission factors – data and assumptions

Pathways uses GHG emission factors for plastic and for substitute materials to provide insight into the climate impacts of the plastic life cycle and of policies aiming to reduce plastic pollution.

5.B.1. Plastic

In addition to human health impacts, Deeney et al., 2023, also provided data on GHG emissions associated with the various stages of the plastic life cycle, by polymer.[48] The data, which are derived using data from the Ecoinvent database 3.8 (cut-off) and the same method combining MFA and LCA described in section 5.A, are expressed in CO_2e per metric ton of plastic and cover the following life-cycle stages:

- Production[49]
  - Pre-polymerization[50]
  - Polymerization
  - Conversion
- Formal collection and transport to sorting plant
- Industrial sorting
- Transportation from sorting to recycling
- International waste trade
- Mechanical recycling
- Chemical recycling (pyrolysis and polymerization for granulate production)
- Avoided burdens of fuel production resulting from pyrolysis
- Incineration
- Controlled landfills
- Open burning
- Dumpsites/uncontrolled landfills
- Terrestrial pollution
- Aquatic pollution

For production GHG emissions, Pathways uses data from a study published by the Lawrence Berkeley National Laboratory (LBNL) on the climate impact of primary plastic production.[51] The LBNL provides a detailed bottom-up accounting of GHG emissions from global plastic production, with a special focus on polymer value chains. The report breaks out life-cycle GHG emissions across all stages of plastic production by polymer type: from extraction of the crude feedstocks, to the production of other chemicals (e.g., methanol), to hydrocarbon refining and processing, monomer production, polymerization and product shaping (e.g., films, fibres). The LBNL data includes both a BAU scenario based on the existing electricity mix reflecting the average global grid GHG emissions intensity, as well as a decarbonized power grid scenario.[52] We summarize GHG emissions from extraction through monomer production to represent virgin materials production, GHG emissions from polymerization to represent the polymerization stage (for which the mass in Pathways includes mass from P2P chemical recycling) and finally product shaping GHG emissions (for which the mass in Pathways includes mass from mechanical recycling being reshaped into new plastic products).

For Pathways, we use virgin polymer production emission factors from the LBNL BAU scenario and use the same emission factors across all geographic archetypes. The GHG emission factors for other life-cycle stages differ across geographic archetypes, based largely on differences in the estimated regional electricity mixes.

5.B.2. Plastic substitutes

The sources of data on GHG emissions associated with plastic substitutes depend on the life-stage modelled:

- Single-use substitute material production emission factors, as well as production emission factors for non-plastic materials used in return/refill systems, are derived from the U.S. Environmental Protection Agency (EPA) Waste Reduction Model (WARM).[53]
- Incineration and landfilling emission factors are derived from EPA WARM.[54]
- Substitute return use-phase emission factors are based on emissions factors from Ellen MacArthur Foundation, 2023, and EPA WARM.[55]
- Collection, sorting and mismanaged waste emission factors for single-use substitute material, materials used for return systems (including plastic) and materials used for refill systems (including plastic) are based on emission factors for plastic in Deeney et al., 2023.[56]

For substitutes production, incineration and landfilling emissions, we obtained data from the WARM tool, version 16.[57] The U.S. EPA developed the WARM tool to inform materials-related decisions with respect to their climate impacts. The tool provides GHG, energy and economic factors developed using a life-cycle approach that considers upstream (virgin material extraction or acquisition), manufacturing, use and end-of-life stages. It is meant to enable comparison across materials and management scenarios (e.g., source reduction, recycling, composting, landfilling, combustion).

For this effort, we used WARM as the source of GHG emission factors for the production of metal, glass, paper and compostable substitutes to plastic (see Table 5-2). These production emissions are based largely on U.S. data and therefore represent life-cycle GHG emissions for materials produced in the United States. This means, for example, that U.S. data underlies the assumed mix of inputs (e.g., share of virgin material versus recyclates), emissions associated with energy inputs, and transportation.

In deriving inputs for Pathways, we used WARM estimates for GHG emissions associated with material source reduction. WARM defines these emissions as those that would be avoided by practices that reduce the amount of materials entering the wastestream. Those are the emissions associated with both producing the material and managing post-consumer waste, i.e., (1) "upstream" GHGs emitted in the raw material acquisition, manufacture, or production and transport of the source-reduced material; (2) amount of carbon stored in forests (when wood and paper products are source reduced); and (3) downstream GHG emissions from waste management. Because Pathways already encompasses GHG emissions associated with end-of-life stages, we focused for this effort on the first source of emissions. Further, given that the data are used in Pathways to capture the GHG implications of increasing materials used as substitutes to plastic, the signs of the emission factors are the opposite of the source reduction factors from WARM.[58]

We converted the WARM emission factors to metric tons of carbon-dioxide equivalent (CO_2e) per metric ton for use in Pathways.

Table 5-2. Production GHG Emission Factors for Plastic Substitutes

Substitute material	WARM materials	% recycled content for current production*	GHG emissions† in metric tons of CO_2e per metric ton of material
Paper	Corrugated containers	35%	6.15
	Mixed paper	23%	6.69
	Average		6.42
Metal	Aluminium cans	68%	5.29
	Mixed metals	33%	4.02
	Average		4.66
Glass	Glass	23%	0.58

* Reflects the current mix of virgin and recycled input in the manufacturing of each product. Emission factors for production from 100% virgin material would be higher.

† Includes process and non-process emissions, as well as transportation emissions (e.g., from combustion of fossil fuels to transport raw materials and intermediate products used in production).

Source: United States Environmental Protection Agency, Office of Resource Conservation and Recovery, *Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM): Management Practices Chapters*, 2023

For incineration and landfilling of substitute materials, we use WARM GHG emission factors that conservatively exclude net avoided emissions from energy recovery and electricity generation, as well as net carbon sequestration in landfills (see Table 5-3). These emission factors include transportation of the material to the incinerator or landfill.

Table 5-3. Incineration and Landfilling GHG Emission Factors for Plastic Substitutes

Substitute material	Incineration GHG emissions ($MTCO_2$e/metric ton material)	Landfilling GHG emissions in metric tons of CO_2e per metric ton of material
Paper	0.055	1.042
Metal	0.011	0.022
Glass	0.011	0.022
Compostables	0.011	0.022

Source: United States Environmental Protection Agency, Office of Resource Conservation and Recovery, *Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM): Management Practices Chapters*, 2023

For other waste management stages (e.g., collection, sorting), we use the same emission factors for substitutes as for plastic.

Data for the return use-phase comes from Ellen MacArthur Foundation, 2023, which provides flow modelling results for four types of single-use packaging and their reusable alternatives.[59] The Ellen MacArthur Foundation estimated GHG emissions associated with the production/conversion of containers, filing, collection, sorting transport, sorting, cleaning, filling transport and end-of-life.[60] As Pathways already includes emissions for single-use packaging and selected life-cycle stages, we focused on those steps that are specific to reuse systems. Table 5-4 presents selected data for the production, conversion, filling, sorting and cleaning of reusable PET and glass bottles. The emissions are based on energy consumption of the machinery and building.[61]

In compiling the GHG emission factors for Pathways, we assumed that the filling, sorting and cleaning of the containers would use highly standardized systems. Filling, sorting and cleaning emission factors from Ellen MacArthur Foundation, 2023, are provided in gCO_2e/unit of reuse material.[62] We converted this to metric tons CO_2 per metric ton of reuse material by dividing the provided emission factors by the weights of reuse units provided by Ellen MacArthur Foundation, 2023 (55 g for reuse plastic, 520 g for reuse glass).[63] We estimated the return cycle transport emissions based on the assumed number of reuse cycles for different materials in Ellen MacArthur Foundation, 2023 (25 cycles for plastic, 50 cycles for glass) and the assumed average weight of a reusable container (55 g for plastic, 520 g for glass).[64]

As no emission factors were available for reusable metal containers, we used the same Ellen MacArthur Foundation, 2023, filing, sorting and cleaning emission factors as glass.[65] For return cycle transport, we used the same starting point as glass for $kgCO_2$ per 1,000 use cycles and assumed 30 use cycles and a weight of 422 g per reusable metal unit.

As discussed later in section 6.D, the application of these emission factors in Pathways accounts for the differences in the weight of materials used for return systems and the container return rate (95%).

Table 5-4. GHG Emission Factors for Return- and Refill-Based Reuse Systems

Stage	Variable	Units	PET bottle	Glass bottle
Filling	High standardization	gCO_2e/unit	0.40	0.50
Sorting	High standardization	gCO_2e/unit	0.11	0.14
Cleaning	High standardization	gCO_2e/unit	3.50	3.50
Return cycle transport	High standardization	$kgCO_2e$/1,000 use cycles	5.00	10.00

Source: Ellen MacArthur Foundation, *Unlocking a Reuse Revolution: Scaling Returnable Packaging—Modelling Technical Appendix*, 2023, p. 41

Table 5-5. Pathways Emission Factors for Return- and Refill-Based Reuse Strategies (gCO2e/g Packaging)

Stage	Return system, by material		
	Plastic	Glass	Metal
Production*	Varies	0.580	4.660

Stage	Return system, by material		
	Plastic	Glass	Metal
Filling[2]	0.007	0.001	0.001
Sorting and washing[†]	0.070	0.010	0.010
Return cycle transport[‡]	2.300	0.960	0.710
Total	Varies	1.550	5.380

* Plastic production stage GHG factors for return plastic are based on the GHG emission factors for PET bottles and depend on the archetype. Glass and metal production stage GHG factors from WARM (see Table 5-2 and Table 5-4).

† Filling, sorting and washing, and return cycle transport from Ellen MacArthur Foundation, *Unlocking a Reuse Revolution: Scaling Returnable Packaging*, 2023. See Table 5-4.

‡ Return cycle transport GHG emissions were estimated based on GHG emissions in Table 5-4.

Source: Ellen MacArthur Foundation, *Unlocking a Reuse Revolution: Scaling Returnable Packaging—Modelling Technical Appendix*, 2023, p. 41

Emission factors for other life-cycle stages come from the following sources:

- Collection: set equal to formal collection emission factors for plastic
- Sorting: set equal to industrial sorting emission factors for plastic
- Mismanaged waste: set equal to open dumpsite/uncontrolled landfill emissions from LDPE/HDPE

5.C. Economic impacts data and assumptions

Pathways uses costs and jobs for plastic and for substitute materials to provide insight into the economic impacts of the plastic life cycle and of policies aiming to reduce plastic pollution. The cost data used in this model was derived from BPW1 and Systemiq, 2023.[66] All costs were adjusted using the Bureau of Labor Statistics Consumer Price Index tables from 2016 to 2023 to be in 2023 US$.[67] All reported costs reflect present values, where future costs and revenues were discounted to 2025 based on a 3.5% discount rate, similar to BPW1.

5.C.1. Macroplastic costs

These data sources provide us with operational expenditures, annualized capital expenditures and jobs per ton of plastic for the following stages in the model:

- Plastic production (applied at flow 54)
- Product shaping/conversion (applied at flows 4, 5, 6)
- Formal collection (applied at flow 12)
- Informal collection and sorting (applied at flows 13, 45)
- Formal sorting (applied at flows 14, 16, 23)
- Mechanical recycling (applied at flows 26, 27, 29, 30)
- Chemical recycling (applied at flows 28, 31)
- Incineration (applied at flow 38)

- Landfilling (applied at flow 39)

Additionally, we have data from the previously mentioned sources on the sales price earned from the following actions in the plastic life cycle:

- Mechanical recycling outputs (applied at flows 32, 55)
- Chemical recycling outputs (applied at flows 35, 37)
- Incineration (applied at flows 38)

5.C.2. Plastic substitute costs

Substitute material costs and jobs are derived from Systemiq, 2023.[68] The costs presented for substitute materials represent the costs per ton of single-use plastic displaced. These costs were converted to costs per ton of substitute material using our assumed weight ratios from Ellen MacArthur Foundation, 2023, and Meng, Brandão and Cullen, 2024, (20 for glass and metal, 1.6 for paper and 0.79 for compostables).[69] All costs were adjusted using the Bureau of Labor Statistics Consumer Price Index tables from 2016 to 2023 to be in 2023 US$.[70]

Table 5-6. Basis of Cost Factors for Substitute Materials

Economic metric	High income	Upper-middle income	Lower-middle- and low income
Capital expenditure (US$2016/metric ton/year)	300.0	300.0	300.0
Operating expenditure, production (US$2016/metric ton/year)	3,449.0	3,449.0	3,449.0
Operating expenditure, waste management (US$2016/metric ton/year)	647.0	324.0	259.0
Jobs (jobs/1,000 metric tons/year)	54.9	54.9	54.9

For return-based reuse systems, we estimated the costs for production, conversion, filling, sorting, washing and return cycle transport using data from Ellen MacArthur Foundation, 2023, and personal communication with Systemiq.[71] These costs were provided as costs per weight of single-use plastic displaced. For this report, we converted these costs to the cost per weight of reuse material using the assumed average use cycles and weight ratios provided in Ellen MacArthur Foundation, 2023, to capture the full costs of reuse systems for the complete lifespan of reuse materials.[72] Systemiq provided these costs for reusable glass and plastic only. Therefore, we assume that metal has the same cost factors as glass. Similarly, we estimated jobs for reuse systems based on the job assumptions provided in Systemiq, 2023.[73] These jobs were also provided in jobs per weight of single-use plastic displaced, which we converted in the same way as the costs. Table 5-7 presents the economic factors used as inputs to Pathways.

Table 5-7. Economic Factors for Return-Based Systems

Economic metric	Reuse plastic	Reuse glass/metal
Capital expenditure (US$2023/metric ton/year)	$5,299.17	$7,267.67

Operating expenditure (US$2023/metric ton/year)	$39,284.50	$9,797.35
Jobs (jobs/1000 metric tons/year)	102.82	10.875

6. Methods for macroplastic System Transformation scenario

6.A. Scenario versions

System Transformation explores the impacts of policy levers targeting macroplastic production, use and waste management in the 10 sectors analysed, as well as microplastic use, design and capture for the seven sources modelled. System Transformation includes three main components: (1) high-level policies affecting plastic use and waste management in the non-packaging sectors; (2) sector-specific policies targeting the packaging sector only; and (3) policies targeting microplastics only. The report presents results for all three components combined, as well as separate results for the packaging-only and microplastics-only policies.

BPW2 includes two versions of System Transformation: a higher-impact scenario ("System Transformation High") and a lower-impact scenario ("System Transformation Low"). These scenarios differ in terms of the underlying assumptions that drive the impact and timeline of each policy lever. To emphasize what could be achieved with significant global collaboration and commitment of resources, we present the System Transformation High results in the main report. The System Transformation Low results generally reflect narrower targets and longer timelines in recognition of the barriers that could hinder progress. The System Transformation Low results are presented in section 10 of this Technical Appendix.

We also model a "System Transformation Delay" scenario to analyse the impacts of delayed action on pollution outcomes and associated impacts. In this scenario, all System Transformation policy start dates and target years (described in the following sections) are shifted forward by five years.

6.B. Constraints

Table 6-1 and Table 6-2 provide the constraints applied in the System Transformation High and System Transformation Low, respectively, alongside the levers for the packaging and non-packaging sectors.

Constraints for chemical recycling in System Transformation High are based on an average of projected growth rates for chemical recycling industry globally and within specific countries, while the System Transformation Low constraints are an average of global projected growth rates for the chemical recycling industry.[74] We assume the LI archetypes experience the same growth rate in chemical recycling as in BAU. For all other constraints for System Transformation High, the growth for HI archetypes is constrained at the highest per capita GDP growth rate from BAU (4.2%), while all other archetypes are set at double the highest per capita GDP growth rate (8.4%). For System Transformation Low, these constraints are set at 75% of the System Transformation High constraints.

Table 6-1. System Transformation High Constraints

Box	% of Year 1	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
11 (formal collection)	100	4.2	4.2	8.4	8.4	8.4	8.4	8.4	8.4
12 (informal collection)	100	4.2	4.2	8.4	8.4	8.4	8.4	8.4	8.4
20 (closed-loop mechanical recycling)	200	4.2	4.2	8.4	8.4	8.4	8.4	8.4	8.4
21 (open-loop mechanical recycling)	200	4.2	4.2	8.4	8.4	8.4	8.4	8.4	8.4
22 (chemical recycling)	500	18.9	18.9	20.6	20.6	20.9	20.9	0.3	0.3
23 (unsorted managed waste)	125	4.2	4.2	8.4	8.4	8.4	8.4	8.4	8.4

Table 6-2. System Transformation Low Constraints

Box	% of Year 1	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
11 (formal collection)	100	3.15	3.15	6.3	6.3	6.3	6.3	6.3	6.3
12 (informal collection)	100	3.15	3.15	6.3	6.3	6.3	6.3	6.3	6.3
20 (closed-loop mechanical recycling)	200	3.15	3.15	6.3	6.3	6.3	6.3	6.3	6.3
21 (open-loop mechanical recycling)	200	3.15	3.15	6.3	6.3	6.3	6.3	6.3	6.3
22 (chemical recycling)	500	13.80	13.80	13.8	13.8	13.8	13.8	0.3	0.3
23 (unsorted managed waste)	125	3.15	3.15	6.3	6.3	6.3	6.3	6.3	6.3

6.C. Non-packaging sectors

6.C.1. Reduction in plastic use

For each of the macroplastic sectors except for packaging, we model a reduction in plastic use (flow 8) associated with System Transformation based on assumptions employed in Felix Cornehl et al., 2024, and OECD, 2024.[75] Table 6-3 presents the target reductions modelled in the System Transformation High scenario; in the System Transformation Low scenario, the targets are reduced by half.

Table 6-3. Reduction in Plastic Use in System Transformation High by Archetype

Sector	HI	UMI	LMI	LI
Agriculture	50%	50%	50%	0%
Building and construction	30%	30%	0%	0%
Consumer and institutional products	20%	20%	20%	20%
Electrical/electronics	50%	50%	0%	0%
Textiles	32%	24%	24%	0%
Transportation	17%	17%	0%	0%
Industrial/machinery	50%	50%	0%	0%
Aquaculture	33%	66%	66%	66%
Fisheries	50%	75%	75%	75%

Sources: Felix Cornehl et al., *Plastic Treaty Futures: Assessing Alternative Scenarios for the Treaty*, 2024, Table 30 (agriculture, building and construction, electrical/electronics, textiles, transportation and industrial/machinery). Felix Cornehl et al., *Plastic Treaty Futures: Assessing Alternative Scenarios for the Treaty*, 2024, Table 34 (aquaculture and fisheries). Organisation for Economic Co-operation and Development, *Policy Scenarios for Eliminating Plastic Pollution by 2040*, 2024, Supplemental Material, Figure 3.3 (consumer and institutional products)

6.C.2. Collection, sorting and recycling

Similarly, downstream flow targets for non-packaging sectors are based on assumptions for the "Global Full Lifecycle" scenario in Felix Cornehl et al., 2024.[76] For System Transformation High, these final targets are achieved by 2040, and in System Transformation Low the targets are achieved by 2045.

Table 6-4. Non-Packaging Sector Downstream Flow Final Targets

Sector	Flow	HI	UMI	LMI	LI
Agriculture	Collection (F10)	98.0%	98.0%	98%	No change from baseline

Sector	Flow	HI	UMI	LMI	LI
	Formal collection for recycling (F14)	50.0%	50.0%	50%	50%
	Incineration (F38)	48.0%	25.0%	No change from baseline	No change from baseline
Fisheries	Collection (F10)	98.0%	96.0%	96%	96%
	Sorting losses (F21)	25.0%	35.0%	35%	35%
	Managed disposal (F25)	100.0%	53.0%	4%	4%
	Formal chemical reprocessing (F28)	10.0%	5.0%	No change from baseline	No change from baseline
	Informal chemical reprocessing (F31)	10.0%	5.0%	No change from baseline	No change from baseline
	Incineration (F38)	48.0%	25.0%	No change from baseline	No change from baseline
Building and construction	Collection (F10)	100.0%	100.0%	100%	100%
	Sorting losses (F21)	45.0%	50.0%	50%	50%
	Managed disposal (F25)	100.0%	55.0%	55%	5%
	Formal closed-loop recycling (F26)	50.0%	50.0%	50%	50%
	Formal chemical reprocessing (F28)	5.0%	2.5%	No change from baseline	No change from baseline
	Informal closed-loop recycling (F29)	50.0%	50.0%	50%	50%

Sector	Flow	HI	UMI	LMI	LI
	Informal chemical reprocessing (F31)	5.0%	2.5%	No change from baseline	No change from baseline
	Incineration (F38)	43.3%	25.0%	33%	No change from baseline
Electronics	Collection (F10)	100.0%	100.0%	100%	100%
	Sorting losses (F21)	80.0%	80.0%	80%	80%
	Managed disposal (F25)	100.0%	50.0%	50%	4%
	Incineration (F38)	43.0%	20.0%	No change from baseline	No change from baseline
Textiles	Collection (F10)	100.0%	100.0%	100%	100%
	Formal collection for recycling (F14)	40.0%	7.5%	15%	No change from baseline
	Sorting losses (F21)	5.0%	40.0%	72%	72%
	Managed disposal (F25)	100.0%	70.0%	70%	50%
	Formal closed-loop recycling (F26)	5.0%	5.0%	5%	5%
	Formal chemical reprocessing (F28)	50.0%	25.0%	No change from baseline	No change from baseline
	Informal closed-loop recycling (F29)	5.0%	5.0%	5%	5%
	Informal chemical reprocessing (F31)	50.0%	25.0%	No change from baseline	No change from baseline

Sector	Flow	HI	UMI	LMI	LI
	Incineration (F38)	50.0%	25.0%	No change from baseline	No change from baseline
Transportation – tyres	Collection (F10)	100.0%	100.0%	100%	100%
	Sorting losses (F21)	41.0%	60.0%	70%	70%
	Managed disposal (F25)	100.0%	55.0%	55%	5%
	Formal chemical reprocessing (F28)	5.0%	2.5%	No change from baseline	No change from baseline
	Informal chemical reprocessing (F31)	5.0%	2.5%	No change from baseline	No change from baseline
	Incineration (F38)	43.0%	25.0%	5%	No change from baseline
Transportation – other	Collection (F10)	100.0%	100.0%	100%	100%
	Sorting losses (F21)	41.0%	50.0%	50%	50%
	Managed disposal (F25)	100.0%	55.0%	55%	5%
	Formal closed-loop recycling (F26)	40.0%	20.0%	20%	20%
	Formal chemical reprocessing (F28)	5.0%	2.5%	No change from baseline	No change from baseline
	Informal closed-loop recycling (F29)	40.0%	20.0%	20%	20%
	Informal chemical reprocessing (F31)	5.0%	2.5%	No change from baseline	No change from baseline

Sector	Flow	HI	UMI	LMI	LI
	Incineration (F38)	43.0%	25.0%	5%	No change from baseline

6.D. Packaging sector

System Transformation includes seven policy levers applied solely to the packaging sector. This section describes the underlying modelling assumptions and parameters for each packaging lever, as well as the methodology used to combine the levers together to create a "stacked" scenario.

As described in this section, modelling assumptions for several levers are based on the expert judgment of the BPW2 expert panel. For example, to estimate the potential for refill-based reuse systems to reduce BAU plastic packaging use, we elicited "feasibility scores" from the experts that correspond to the demand reduction that could be achieved under System Transformation High and System Transformation Low. In assigning the scores, we asked the experts to consider factors such as affordability, convenience and whether the intervention would satisfy performance and health requirements. Experts provided scores for the HI archetype and non-HI archetypes separately to reflect variations in feasibility depending on income and other limiting factors. These scores were then applied in System Transformation High and System Transformation Low to reflect different assumptions about levels of reduction and transition over time.

6.D.1. Ban lever

The ban lever models the reduction in BAU plastic production and use that could result from banning PS, EPS and PVC use in packaging products by 2040. We assume a ban on specific polymers will result in a corresponding shift in the packaging industry to producing or importing other polymers to replace the mass reduced by the banned ones. We further assume that the packaging industry will gradually and incrementally phase out the banned polymers and shift to alternative polymers by the target year on which the polymer ban is fully implemented. To model this lever, we phase out the BAU demand for the banned polymers in each of the packaging plastic categories linearly between 2025 and 2040, shifting the phased-out BAU demand to the remaining polymers within each plastic packaging category. As shown in Table 6-5, all plastic packaging categories are affected by the polymer ban except PET Bottles, which do not include either of the banned polymers.

Table 6-5. Ban Lever Demand Shift

BPW2 plastic packaging category	BAU polymer demand	Polymer demand shift under ban lever
PET bottles	HDPE, PP, PET	N/A – no PS/EPS or PVC in BAU
Other bottles	LDPE/LLDPE, HDPE, PP, PVC, PET	Shift the demand for PVC equally across LDPE, HDPE, PP and PET

Rigid food packaging	Other, LDPE/LLDPE, HDPE, PP, PS/EPS, PVC, PET	Shift the demand for PS/EPS and PVC equally across Other, LDPE, HDPE, PP and PE
Rigid non-food packaging	Other, LDPE/LLDPE, HDPE, PP, PS/EPS, PVC, PET	Shift the demand for PS/EPS and PVC equally across Other, LDPE, HDPE, PP and PE
Flexible packaging	Other, LDPE/LLDPE, HDPE, PP, PS/EPS, PVC, PET	Shift the demand for PS/EPS and PVC equally across Other, LDPE, HDPE, PP and PE
Multilayer packaging	Other, LDPE/LLDPE, PP, PVC, PET	Shift the demand for PVC equally across Other, LDPE/LLDPE, PP and PET

6.D.2. Eliminate lever

The eliminate lever models the reduction in BAU plastic production and use that could result from eliminating unnecessary plastic packaging (without replacing it with packaging made of substitute materials). This lever targets excess packaging such as films or bags used to separate or wrap individual items for sale, which could otherwise be kept together or left unwrapped.

To estimate the percentage of BAU demand that could be eliminated within each BPW2 plastic packaging category and archetype, we applied the scoring system used in the BPW1 modelling scenarios. Specifically, we relied on the "eliminate" scores presented in Table S22 of the BPW1 Supplementary Material.[77] Table 6-6 presents the eliminate lever scores by archetype group and packaging product category and the sources informing them. Note that the plastic categories analysed in BPW1 differed from the BPW2 categories; for each BPW2 category, we identified the BPW1 product category for which we adopted the eliminate scores. These scores range from 1 to 4 and map to specific target percentage reductions in BAU demand by the target year under the high and low ambition scenarios.

Table 6-6. Eliminate Lever Scores

BPW2 plastic packaging category	Score for HI archetype	Score for UMI, LMI and LI archetypes	Source
PET beverage bottles	1	1	BPW1 score for water bottles
Other bottles	1	1	BPW1 score for other bottles
Rigid food packaging	3	3	BPW1 score for fresh fruit/vegetable tray/pot/punnet/tub
Rigid non-food packaging	2	2	BPW1 score for rigid household goods
Flexible packaging	2	2	BPW1 score for films

Multilayer packaging	2	2	BPW1 score for multilayer flexibles

Sources: Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020. Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

Table 6-7 provides the score definitions that specify the percentage reduction in plastic demand by 2040 corresponding to each score. Under System Transformation High, the reduction in demand ranges from 0% (score of 1) to 80% (score of 4). These score definitions mirror those employed in the BPW1 modelling. For System Transformation Low, we reduced the demand reduction targets under System Transformation High by half.

Table 6-7. Eliminate Lever Score Definitions

Score	Percentage of BAU demand reduced by 2040	
	System Transformation High	System Transformation Low
1	0%	0%
2	10%	5%
3	50%	25%
4	80%	40%

Source: Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020

To model the eliminate lever, we applied a linear reduction in the BAU plastic demand mass flows for each of the plastic packaging categories based on the archetype and packaging product-specific scores in Table 6-6. The linear reduction takes place beginning in 2025 and ends in 2040 with the achievement of the corresponding target demand reduction specified in Table 6-7 for each ambition level. The demand shifts for the packaging products under the eliminate lever are applied consistently across zones (i.e., urban and rural).

6.D.3. Return-based reuse lever

The return-based reuse lever models the reduction in plastic packaging use that could result from widespread adoption of return-based reuse systems for plastic packaging. As defined in Ellen MacArthur Foundation, 2019, there are four primary reuse models: (1) refill at home; (2) refill on-the-go; (3) return from home; and (4) return on-the-go.[78] This lever focuses on the fourth reuse model, return on-the-go, in which users purchase products in reusable packaging and then return them to a store or drop-off point (e.g., in a deposit return machine). The reusable packaging is then collected, transported to a facility for sorting, washing and refilling, and then redistributed. This reuse model is widely applicable to various types of single-use plastic (SUP) packaging and has been proven effective at scale in several geographies.[79] For this lever, we analysed the potential impacts of replacing SUP packaging with reusable, returnable packaging made of plastic, glass, or metal. We assume this lever would target an archetype, reuse material and packaging product-specific percentage reduction in BAU plastic demand by two target years (2035 and 2040), based on the ambition level. We further assume the packaging industry and consumers will gradually and incrementally shift to the return-based reuse system to meet the target reductions and years.

To estimate the percentage of the SUP packaging that could be replaced with reusable packaging in a return-based reuse system (i.e., the modelled demand reduction achieved by return-based reuse), we relied on expert judgment. We employed the same scoring approach as in the eliminate lever (based on the approach employed in BPW1), eliciting feasibility scores from the BPW2 expert panel for each BPW2 packaging product category, archetype and material. In assigning scores, the experts considered factors such as affordability, convenience and whether the intervention would satisfy performance and health requirements. After receiving individual scores from multiple members of the expert panel, we averaged the scores to produce a single score for each plastic packaging type, return material and archetype category (Table 6-8).

Table 6-8. Return-Based Reuse Lever Scores

BPW2 plastic packaging category	Score for HI archetype			Score for UMI, LMI and LI archetypes		
	Plastic	Metal	Glass	Plastic	Metal	Glass
PET beverage bottles	4	1	4	3	1	4
Other bottles	3	1	4	3	1	3
Rigid food packaging	3	2	2	3	2	2
Rigid non-food packaging	3	2	1	2	1	1
Flexible packaging	2	1	1	1	1	1
Multilayer packaging	2	1	1	1	1	1

Source: Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

Table 6-9. Return-Based Reuse Lever Score Definitions

Score	System Transformation High		System Transformation Low	
	Percentage of BAU demand reduced by 2035	Percentage of BAU demand reduced by 2040	Percentage of BAU demand reduced by 2035	Percentage of BAU demand reduced by 2040
1	0%	0%	0%	0%

2	1%	10%	1%	5%
3	20%	50%	10%	25%
4	50%	80%	25%	40%

Sources: Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020. Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

We applied a two-pronged linear reduction approach to achieve target percentage reductions in BAU demand by two target years, 2035 and 2040, under System Transformation High and System Transformation Low (as defined in Table 6-9). We account for the material-specific proportion of the total BAU percentage demand reduction across all return-based reuse materials by applying a weighted scaling approach. This approach distributes the BAU demand reduction proportionally across materials, scaling the BAU demand shifts accordingly. We assume that the initial BPW2 plastic packaging category adopts the behaviour (i.e., scores) of the corresponding return-based reuse material.

For example, in the case of "other bottles" in the UMI, LMI and LI archetypes, the metal return-based reuse material has a score of 1, corresponding to a percentage BAU demand reduction of 0%. As a result, only plastic and glass, whose scores correspond to non-zero percentage BAU demand reductions, are considered in their contributions to the total BAU demand reduction. In the low-ambition scenario, shifts from other bottles to plastic has a score of 3 and to glass has a score of 3 in low- and middle-income archetypes, indicating that up to 10% of the demand for other bottles could be shifted to plastic or glass return materials by 2035. By 2040, these BAU demand reductions are up to 25%.

In this example, the maximum reduction is 10% (2035) and 25% (2040), corresponding to a score of 3 for plastic or glass, depending on the target year. This maximum demand reduction is then split between the relevant return-based reuse materials, weighted by the sum of their demand shift potentials. The equation below indicates how we calculated the applied demand shift for each return-based reuse material.

$$applied\ shift_{ti} = \max(demand\ shift_t) \times \frac{demand\ shift_{ti}}{sum(demand\ shift_t)}$$

where

i is the specific return-based reuse material being shifted to,

t is the target year (2035 or 2040),

$applied\ shift$ is the demand shift used in the model,

$demand\ shift_{ti}$ is the potential demand shift for a given return-based reuse material within a certain target year and

$\max(demand\ shift_t)$ is the largest potential demand shift for a given target year (within an archetype).

We consider the maximum material-specific percentage BAU demand reduction because it indicates the overall potential of the plastic single-use product to be shifted to other materials. The resulting percentage changes in BAU demand reflect relative shifts from the BAU BPW2 plastic packaging category to return-based reuse materials. Table 6-10 provides example scores and how the BAU demand shifted would be allocated to the various return material types based on the method described above. This method applies both to the refill and substitute levers as well.

Table 6-10. Example Scores and Associated Allocated Demand Shifts

Example scores	Maximum BAU demand shifted by 2040 (System Transformation High)	Share of maximum shifted demand allocated to each material (%)
4/4/1	80%	50/50/0
4/3/2	80%	57/36/7
3/2/1	50%	83/17/0
2/2/2	10%	33/33/33

We assume that shifting demand to alternative materials could have disproportional mass implications. To account for this, we applied a material-specific increase in consumption for the plastic, glass and metal reuse materials needed to meet the target annual percentage shift in BAU demand. Specifically, we estimated the mass of each reuse material needed to create reusable packaging. Because reusable packaging is heavier than SUP, we applied weight ratios of SUP packaging to reusable plastic, glass and metal packaging in each of the BPW2 plastic packaging categories. Table 6-11 presents the resulting weight ratios and source(s) for each estimate. Note that in calculating each ratio, we employed weight data for comparable SUP and reusable packaging (i.e., packaging serving the same function and with the same capacity).

Table 6-11. Weight Ratios of SUP to Reusable Materials

BPW2 plastic packaging category	Reusable plastic		Reusable glass		Reusable metal	
	Weight ratio	Source	Weight ratio	Source	Weight ratio	Source
PET beverage bottles	2.1	Weight data for SUP and reusable PET bottles from Ellen MacArthur Foundation, 2023	16.5	Weight data for SUP and glass water bottles from Deeney et al., 2023	16.2	Based on measured weight of 1 litre metal Klean Kanteen water bottle (422 g) and weight of SUP PET bottle from Ellen MacArthur Foundation, 2023
Other bottles	2.1	Weight data for SUP and reusable PE personal care bottles from Ellen MacArthur Foundation, 2023	16.5	No data; applied weight ratio for PET beverage bottles	16.2	No data; applied weight ratio for PET beverage bottles
Rigid food packaging	2.0	Weight data for SUP and reusable PP fresh food packaging from Ellen MacArthur Foundation, 2023	4.4	Weight data for SUP and glass off-premise food packaging from Deeney et al., 2023	12.2	Weight data for stainless steel and single-use PLA sushi boxes from Bradbury et al., 2023
Rigid non-food packaging	2.0	No data; applied weight ratio for rigid food packaging	4.4	No data; applied weight ratio for rigid food packaging	12.2	No data; applied weight ratio for rigid food packaging
Flexible packaging	5.0	Weight data for SUP and reusable flexible PP food-cupboard packing from Ellen MacArthur Foundation, 2023	4.3	Weight data for SUP and glass flexibles from Deeney et al., 2023	12.2	No data; applied weight ratio for rigid food packaging

Multilayer packaging	5.0	No data; applied weight ratio for flexible packaging	4.3	Weight data for SUP and glass multilayer from Deeney et al., 2023	12.2	No data; applied weight ratio for rigid food packaging

Sources: Ellen MacArthur Foundation, *Unlocking a Reuse Revolution: Scaling Returnable Packaging—Design Pathways Appendix*, 2023. Megan Deeney et al., *Global Health Impacts of Addressing the Plastic Pollution Crisis: A Life Cycle Approach*, 2023. John Bradbury et al., *Assessing Climate Impact: Reusable Systems vs. Single-Use Takeaway Packaging*, 2023.

Additionally, we account for the return and reuse of the plastic, metal and glass reusable packaging over a specified number of return cycles, based on the material-specific ability to sustain reuse over its lifetime. Based on expert judgment, we estimated that reusable plastic packaging could sustain 20 return cycles, reusable glass packaging could sustain 12 return cycles and reusable metal packaging could sustain 30 return cycles. We assume the same number of return cycles across all plastic packaging types modelled. We calculate this lifetime ratio as the inverse of the number of return cycles and apply it annually to the percentage shift in BAU demand to account for the useful life of each return-based reuse material.

Finally, we assume a surplus BAU demand to account for a proportion of the shift in BAU demand that would be lost as waste due to compliance or processing (i.e., sorting and cleaning) shortfalls with the return model. Therefore, we estimate a return rate of 95% based on assumptions in Ellen MacArthur Foundation, 2023.[80] We account for surplus BAU demand to cover the mass lost (5%) from the 95% return rate by proportionally increasing the weight ratio for each alternative material per year.

We also estimate the climate change and economic impacts associated with the return-based reuse policy lever. See section 5.B.2 for more information on estimating the GHG emissions associated with return-based reuse systems and section 5.C.2 for information on estimating the economic factors for return-based reuse systems.

6.D.4. Refill-based reuse lever

The refill-based reuse lever models the reduction in plastic packaging use that could result from widespread adoption of refill-based reuse systems for plastic packaging. As defined in Ellen MacArthur Foundation, 2019, there are four primary reuse models: (1) refill at home, (2) refill on-the-go, (3) return from home and (4) return on-the-go.[81] This lever focuses on the second reuse model, refill on-the-go, in which users refill their reusable containers away from home (e.g., at an in-store dispensing system). The reusable packaging may take the form of an existing container or a new one that is purchased and then reused. For this lever, we analysed the potential impacts of replacing SUP packaging with reusable, refillable packaging made of plastic, glass or metal. We assume this lever would target an archetype, reuse material and packaging product-specific percentage reduction in BAU plastic demand by two target years (2035 and 2040), based on the ambition level. We further assume the packaging industry and consumers will gradually and incrementally shift to the refill-based reuse system to meet the target reductions and years.

To estimate the percentage of the SUP packaging that could be replaced with reusable packaging in a refill-based reuse system (i.e., the modelled demand reduction achieved by refill-based reuse), we relied on expert judgment. We employed the same scoring approach as in the eliminate lever (based on the approach employed in BPW1), eliciting feasibility scores from the BPW2 expert panel for each BPW2 packaging product category, archetype and material. In assigning scores, the experts considered factors such as affordability, convenience and whether the intervention would satisfy performance and health requirements. After receiving individual scores from multiple members of the expert panel, we averaged the scores to produce a single score for each plastic packaging type, refill material and archetype category (Table 6-12).

Table 6-12. Refill-Based Reuse Lever Scores

BPW2 plastic packaging category	Scores for HI archetype			Scores for UMI, LMI and LI archetypes		
	Plastic	Metal	Glass	Plastic	Metal	Glass
PET beverage bottles	3	3	2	3	3	1
Other bottles	3	3	2	3	3	1
Rigid food packaging	3	2	2	3	2	1
Rigid non-food packaging	2	2	2	2	2	1
Flexible packaging	3	2	1	3	2	1
Multilayer packaging	2	2	1	2	1	1

Source: Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

Table 6-13. Refill-Based Reuse Lever Score Definitions

Score	System Transformation High		System Transformation Low	
	Percentage of BAU demand reduced by 2035	Percentage of BAU demand reduced by 2040	Percentage of BAU demand reduced by 2035	Percentage of BAU demand reduced by 2040
1	0%	0%	0%	0%
2	1%	10%	1%	5%
3	20%	50%	10%	25%
4	50%	80%	25%	40%

Sources: Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020.

As in the return-based reuse lever, we applied a two-pronged linear reduction approach to achieve target percentage reductions in BAU demand by two target years, 2035 and 2040, under System Transformation High and System Transformation Low (as defined in Table 6-13). We account for the material-specific proportion of the total BAU percentage demand reduction across all refill-based reuse materials by applying a weighted scaling approach. This approach distributes the BAU demand reduction proportionally across materials, scaling the BAU demand shifts accordingly. We assume that the initial BPW2 plastic packaging category adopts the behaviour (i.e., scores) of the corresponding refill-based reuse material.

We consider the maximum material-specific percentage BAU demand reduction because it indicates the overall potential of the plastic single-use product to be shifted to other materials. The resulting percentage changes in BAU demand reflect relative shifts from the BAU BPW2 plastic packaging category to refill-based reuse materials.

To model the refill-based reuse lever, we first applied linear reductions in BAU plastic demand for each plastic packaging category based on the scores in Table 6-12 and score definitions in Table 6-13. We follow the two-pronged linear reduction approach from the return-based reuse lever to estimate the per-year percentage reductions in BAU demand required to achieve the target BAU demand percentage reduction by both target years (2035 and 2040). The percentage demand shifts for the packaging products under the refill lever are applied consistently across zones (i.e., urban and rural).

Next, we estimated the percentage of the refill-based reuse system that would be met using existing refillable packaging (rather than requiring the production of new refillable containers). Table 6-14 presents these pre-existing mass estimates, which are based on expert judgment from the BPW2 Expert Panel. For the lower-middle- and low-income archetypes, we estimate that all packaging used in the refill-based reuse systems is pre-existing (i.e., that there is no need for the production of new refillable packaging, and consumers will use their own pre-existing containers). For the upper-middle- and high-income archetypes, we estimate that between 0% and 90% of the refillable packaging is pre-existing, depending on the packaging category.

Table 6-14. Percentage of Refillable Packaging That Is Pre-Existing by Geographic Archetype

BPW2 plastic packaging category	High income	Upper-middle income	Lower-middle income	Low income
PET beverage bottles	90%	90%	100%	100%
Other bottles	0%	0%	100%	100%
Rigid food packaging	90%	90%	100%	100%
Rigid non-food packaging	50%	50%	100%	100%
Flexible packaging	50%	50%	100%	100%
Multilayer packaging	0%	0%	100%	100%

Source: Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

Based on the refill scores, refill score definitions and the estimated percentage of refillable packaging that is pre-existing, we then modelled a material-specific increase in consumption for plastic, glass and metal reuse materials needed to meet the target annual percentage shift in BAU demand. Using the same approach and weight ratios (see Table 6-11) as the return-based reuse lever, we accounted for the mass of each reuse material needed to create reusable packaging. We multiply the material-specific weight ratios by the inverse of their corresponding percentage of pre-existing mass to account for existing refill containers that would not need to be newly produced.

Similar to the return-based reuse lever, we account for the refill and reusability of alternative materials over several refill cycles based on the material-specific ability to sustain reuse over its lifetime. Table 6-15 provides the number of cycles each refill-based reuse material could sustain for each plastic packaging category based on expert judgment. We calculate this lifetime ratio as the inverse of the number of refill cycles and apply it annually to the percentage shift in BAU demand to account for the useful life of each refill-based reuse material. We did not model impacts (GHG, economic) associated with the user's transportation to points of purchase or with cleaning their containers.

Table 6-15. Number of Cycles Assumed for Refill-Based Reuse System

	Number of cycles		
BPW2 plastic packaging category	**Plastic**	**Glass**	**Metal**
PET beverage bottles	200	200	200
Other bottles	35	35	35
Rigid food packaging	30	30	30
Rigid non-food packaging	30	30	30
Flexible packaging	30	30	30
Multilayer packaging	30	30	30

Source: Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

6.D.5. Substitute lever

The substitute lever models the reduction in SUP packaging use that could result from scaling up substitution of SUP packaging with single-use packaging made of substitute materials, including glass, metal, paper and compostables. In addition, we analysed the potential impacts of "upgrading" plastic used in SUP packaging to more recyclable plastic types. To estimate the percentage of BAU demand that could be replaced with substitutes within each BPW2 plastic packaging category and archetype, we relied on the judgment of the BPW2 Expert Panel to inform a substitute scoring system. We employed the same scoring approach as the reuse levers, obtaining scores by BPW2 plastic category, archetype and substitute material (Table 6-16). These scores correspond to high- and low-ambition percentage reductions in BAU demand by 2035 and 2040 (Table 6-17).

Table 6-16. Substitute Lever Scores

BPW2 plastic packaging category	Scores for HI archetype				Scores for UMI, LMI and LI archetypes			
	Glass	Metal	Paper	Compostables	Glass	Metal	Paper	Compostables
PET beverage bottles	3	3	2	1	2	2	2	1
Other bottles	3	3	2	1	2	2	2	1
Rigid food packaging	2	3	3	2	2	2	2	2
Rigid non-food packaging	2	2	3	2	2	2	2	2
Flexible packaging	1	1	3	3	1	1	3	3
Multilayer packaging	1	1	3	3	1	1	2	3

Source: Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

Table 6-17. Substitute Lever Score Definitions

Score	System Transformation High		System Transformation Low	
	Percentage of BAU demand reduced by 2035	Percentage of BAU demand reduced by 2040	Percentage of BAU demand reduced by 2035	Percentage of BAU demand reduced by 2040
1	0%	0%	0%	0%
2	1%	10%	1%	5%
3	20%	50%	10%	25%
4	50%	80%	25%	40%

Source: Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020

Like the reuse levers, we account for the material-specific proportion of the total BAU percentage demand reduction across all substitute materials by applying a weighted scaling approach to distribute the BAU demand reduction proportionally across materials. We assume that the substituted proportion of the initial BPW2 plastic packaging category adopts the behaviour (i.e., scores) of the corresponding substitute material.

For example, in the case of multilayer packaging in low- and middle-income archetypes, glass and metal substitutes have scores of 1, corresponding to a percentage BAU demand reduction of 0%. As a result, only paper and compostables, whose scores correspond to non-zero percentage BAU demand reductions, are considered in their contributions to the total BAU demand reduction. In the high-ambition scenario, shifts from multilayer packaging to paper or compostables (since they have the same score) in low- and middle-income archetypes each account for up to 1% of the BAU demand reduction by 2035. By 2040, these contributions each account for up to 10% BAU demand reduction. Since both materials have the same score, the weighted demand shift to each substitute material will be half of the target demand reduction.

This weighted percentage demand reduction is then multiplied by the maximum percentage reduction in BAU demand across the substitute materials being considered. In this example, since paper and compostables have the same scores, the maximum reduction is 1% or 10%, depending on the target year. The percentage of a given single-use plastic type then shifting to either paper or compostables is then 0.5% or 5%, depending on the target year, totaling the maximum reduction. The resulting percentage changes in BAU demand reflect relative shifts from the BAU BPW2 plastic packaging category to substitute materials.

For SUP packaging types that require a different design or format of plastic to be recyclable, we applied material changes to model an upgrade for the plastic substitute material. For example, PET beverage bottles are already highly recyclable and would not require a different plastic to be recycled, while other bottles would need to be replaced by a plastic format similar to PET beverage bottles to be more recyclable. Table 6-18 presents the crosswalk between BPW2 plastic packaging types and their upgraded substitute plastic materials.

Table 6-18. Plastic Upgrade Matrix

BAU BPW2 plastic packaging category	Upgrade with lever
PET beverage bottles	None
Other bottles	PET beverage bottles
Rigid food packaging	None
Rigid non-food packaging	None
Flexible packaging	Rigid non-food packaging
Multilayer packaging	Flexible packaging

Source: Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

Given that demand will also shift to substitute materials to achieve the target-year goals, we relied on the BPW2 Expert Panel to estimate the relative percentage of BAU demand that will shift to the upgraded plastic type by the target years. We employed the same scoring approach as the other substitute materials, obtaining scores by BPW2 plastic category and archetype, as shown in Table 6-19. These scores correspond to high and low ambition-based relative percentage shifts in BAU demand to an upgraded, more recyclable plastic by 2035 and 2040, as shown in Table 6-20. The percentage changes in BAU demand reflect relative shifts from the BAU BPW2 plastic packaging category to recyclable plastic.

For BPW2 plastic packaging categories that require upgrades, we look up the initial (non-upgraded) plastic categories in Table 6-18 to identify the amount to shift to an upgraded plastic. Therefore, BPW2 plastic categories that do not require upgrades (i.e., PET beverage bottles, rigid food packaging and rigid non-food packaging) have scores of 1, corresponding to a 0% shift to a more recyclable plastic. For example, other bottles have a score of 2 (for both archetypes), corresponding to a BAU demand shift of 1% and 10% or 1% and 5% based on the archetype for 2035 and 2040, respectively, to PET beverage bottles.

Table 6-19. Plastic Upgrade Scores

BPW2 plastic packaging category	Scores for HI archetype	Scores for UMI, LMI and LI archetypes
PET beverage bottles	1	1
Other bottles	2	2
Rigid food packaging	1	1
Rigid non-food packaging	1	1
Flexible packaging	2	2
Multilayer packaging	2	2

Source: Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

Table 6-20. Plastic Upgrade Score Definitions

	System Transformation High		System Transformation Low	
Score	Percentage of BAU demand shifted to upgraded plastic type by 2035	Percentage of BAU demand shifted to upgraded plastic type by 2040	Percentage of BAU demand shifted to upgraded plastic type by 2035	Percentage of BAU demand shifted to upgraded plastic type by 2040
1	0%	0%	0%	0%
2	1%	10%	1%	5%
3	20%	50%	10%	25%
4	50%	80%	25%	40%

Source: Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020

Because recyclable packaging is heavier than SUP, we applied weight ratios of comparable SUP packaging to recyclable plastic packaging for each of the BPW2 plastic packaging categories requiring an upgraded plastic type. Table 6-21 presents the resulting weight ratios and data source(s) for each estimate.

Table 6-21. Weight Ratios for Plastic Upgrades

Scenario	Weight ratio for substitution with more recyclable plastic	Source
Upgrading from other bottles to PET bottles	1.4	Calculated based on the ratio of the average weight of LDPE, HDPE and PVC bottles to the weight of a PET bottle.
Upgrading from flexible packaging to rigid non-food packaging	11.9	Calculated based on the ratio of the weight of a gallon plastic zipper bag to a gallon rigid HDPE container.
Upgrading from multilayer packaging to flexible packaging	1	No data available; assumed 1.

Sources: Berlin Packaging, *16 Oz Clear PET Plastic Beverage Bottles*. Berlin Packaging, *1 Gal Natural HDPE Plastic Round Snap-Lock Containers*

Similarly, we calculated and applied weight ratios for the other substitute materials to account for weight differences between the BAU SUP category and the single-use substitute materials. Table 6-22 presents the resulting weight ratios and source(s) for each estimate.

Table 6-22. Weight Ratios of SUP to Single-Use Substitute Materials

BPW2 plastic packaging category	Single-use metal		Single-use glass		Single-use compostables		Single-use paper	
	Weight ratio	Source	Weight ratio	Source	Weight ratio	Source	Weight ratio	Source
PET beverage bottles	0.9	Calculated based on weight data for PET bottle and aluminum can from Meng, Brandão and Cullen, 2024	14.2	Calculated based on weight data for PET bottle and glass bottle from Meng, Brandão and Cullen, 2024	0.8	Calculated based on weights of 500 ml PLA and PET bottle provided on retailer websites	1.6	Calculated based on weight data for HDPE and paper milk containers from Meng, Brandão and Cullen, 2024
Other bottles	0.9	No data; applied weight ratio for beverage bottles	14.2	No data; applied weight ratio for beverage bottles	0.8	No data; applied weight ratio for beverage bottles	1.6	No data; applied weight ratio for beverage bottles
Rigid food packaging	0.9	No data; applied weight ratio for beverage bottles	14.2	No data; applied weight ratio for beverage bottles	0.8	No data; applied weight ratio for beverage bottles	1.6	No data; applied weight ratio for beverage bottles
Rigid non-food packaging	0.9	No data; applied weight ratio for beverage bottles	14.2	No data; applied weight ratio for beverage bottles	0.8	No data; applied weight ratio for beverage bottles	1.6	No data; applied weight ratio for beverage bottles
Flexible packaging	3.3	No data; applied weight ratio for multilayer packaging	14.2	No data; applied weight ratio for beverage bottles	0.8	No data; applied weight ratio for beverage bottles	1.6	No data; applied weight ratio for beverage bottles
Multilayer packaging	3.3	Calculated as the average of weight ratios of SUP multilayer pouch to aluminium and steel, based on data	14.2	No data; applied weight ratio for beverage bottles	0.8	No data; applied weight ratio for beverage bottles	1.6	No data; applied weight ratio for beverage bottles

		from Meng, Brandão and Cullen, 2024						

Sources: Fanran Meng, Miguel Brandão, and Jonathan M. Cullen, *Replacing Plastics With Alternatives Is Worse for Greenhouse Gas Emissions in Most Cases*, 2024. Berlin Packaging, *16 Oz Clear PET Plastic Beverage Bottles.* NaKu, *Naku – Made of Natural Plastic*

Like the reuse levers, we estimated percentage changes in BAU demand per year to then be applied to the adjusted mass flows from the ban and eliminate levers in System Transformation. This allowed for modelling each lever independently before combining them in System Transformation. To model the substitute lever, we first applied linear reductions in BAU plastic demand for each plastic packaging category based on the scores and score definitions. We follow the two-pronged linear reduction approach used in the reuse levers to estimate the per-year percentage reductions in BAU demand (and corresponding increases in substitute materials or recyclable plastic) required to achieve the target BAU demand percentage reduction by both target years (2035 and 2040). To reflect the substitute material options and the plastic upgrade, the per-year BAU percentage demand reductions are shifted to the substitute materials proportionally, as described earlier. The percentage demand shifts for the packaging products under the substitute lever are applied consistently across zones (i.e., urban and rural).

See sections 5.B.2 and 5.C.2 for a summary of how economic and climate impacts were estimated for substitute materials.

6.D.6. Collection lever

The collection lever models the impacts associated with increasing the share of plastic packaging waste that gets collected and sent to managed disposal. The targets, shown in Table 6-23, were developed by Equanimator, 2024, to inform the Intergovernmental Negotiating Committee (INC) negotiations. [82] In parallel to the modelling to achieve these targets, Pathways includes the changes to constraints on incineration and landfill as described in section 6.B.

Table 6-23. Modelling Targets for Collection Lever

Archetype	Baseline collection rate	Target collection rate				Baseline managed disposal rate	Target managed disposal rate			
		High System Transformation	Years to high target	Low System Transformation	Years to low target		High System Transformation	Years to high target	Low System Transformation	Years to low target
HI-R	99.70%	No change	3	None	None	99.90%	100%	3	100%	6
HI-U	99.80%	No change	3	None	None	99.90%	100%	3	100%	6
LI-R	30.58%	95.0%	10	70%	20	0.00%	100%	10	100%	20
LI-U	46.18%	99.8%	8	85%	16	1.00%	100%	8	100%	16
LMI-R	49.76%	95.0%	8	85%	16	1.50%	100%	8	100%	16
LMI-U	74.28%	99.8%	8	85%	16	7.50%	100%	8	100%	16
UMI-R	62.91%	95.0%	8	85%	16	60.80%	100%	8	100%	16
UMI-U	90.84%	99.8%	3	None	None	77.00%	100%	3	100%	6

6.D.7. Recycling lever

The collection lever models the impacts associated with increasing the share of plastic packaging waste that gets recycled and the share of recycled waste that goes to closed-loop mechanical and chemical recycling (versus open-loop). The targets, shown in Table 6-24, were developed based on the analysis in Equanimator, 2024, to inform INC negotiations. [83] In parallel to the modelling to achieve these targets, Pathways includes the changes to constraints on incineration and landfill as described in section 6.B.

Table 6-24. Modelling Assumptions for System Transformation Packaging Recycling Lever

Arche type	BPW2 plastic packaging type	Target recycling rate	Years from 2025 to reach recycling target		Target rate of formal collection to closed-loop		Target rate of informal collection to closed-loop		Target rate of formal to chemical recycling		Target rate of informal to chemical recycling		Target rate of P2P	
			System Transformation High	System Transformation Low	System Transformation High	System Transformation Low	System Transformation High	System Transformation Low	System Transformation High	System Transformation Low	System Transformation High	System Transformation Low	System Transformation High	System Transformation Low
HI-R, HI-U, UMI-U	PET bottles	80%	3	6	72%	69%	84%	79%	0%	0%	0%	0%	45%	20%
	Other bottles	70%	6	12	72%	69%	84%	79%	0%	0%	0%	0%	45%	20%
	Rigid food packaging	60%	6	12	72%	69%	84%	79%	0%	0%	0%	0%	45%	20%
	Rigid non-food packaging	60%	6	12	72%	69%	84%	79%	0%	0%	0%	0%	45%	20%
	Flexible packaging	50%	6	12	33%	29%	42%	26%	50%	25%	0%	0%	45%	20%
	Multilayer packaging	50%	6	12	0%	0%	0%	0%	50%	25%	0%	0%	45%	20%
LI-R	PET bottles	80%	12	24	0%	0%	37%	32%	0%	0%	0%	0%	45%	20%

	Other bottles	70%	12	24	0%	0%	37%	32%	0%	0%	0%	0%	45%	20%
	Rigid food packaging	60%	12	24	0%	0%	37%	32%	0%	0%	0%	0%	45%	20%
	Rigid non-food packaging	60%	12	24	0%	0%	37%	32%	0%	0%	0%	0%	45%	20%
	Flexible packaging	50%	12	24	0%	0%	11%	11%	0%	0%	0%	0%	45%	20%
	Multilayer packaging	50%	12	24	0%	0%	0%	0%	0%	0%	0%	0%	45%	20%
LI-U, LMI-U, LMI-R, UMI-R	PET bottles	80%	5	10	22%	14%	37%	32%	0%	0%	0%	0%	45%	20%
	Other bottles	70%	10	20	22%	14%	37%	32%	0%	0%	0%	0%	45%	20%
	Rigid food packaging	60%	10	20	22%	14%	37%	32%	0%	0%	0%	0%	45%	20%
	Rigid non-food packaging	60%	10	20	22%	14%	37%	32%	0%	0%	0%	0%	45%	20%

	Flexible packaging	50%	10	20	22%	14%	21%	16%	50%	25%	11%	5%	45%	20%
	Multilayer Packaging	50%	10	20	0%	0%	0%	0%	50%	25%	11%	5%	45%	20%

6.D.8. Combining the levers

System Transformation assumes that the levers will be organized and implemented such that the targets and their effects on the mass flow of plastic will be interdependent rather than independently achieved. While we described the eliminate and ban levers separately in this Technical Appendix, we modelled them together as an overall eliminate lever for the packaging sector, encompassing both product and polymer bans in an overall BAU demand shift per year and BPW2 plastic packaging category. We consider that System Transformation would affect two groups of flows: upstream and downstream. Because the upstream packaging levers (eliminate, return, refill and substitute) impact the same flows, representing BAU demand, System Transformation combines and models their effects on mass flows sequentially based on the feasibility and in alignment with the waste hierarchy in a comprehensive scenario achieving all lever-specific targets. [84] We assume that System Transformation would first eliminate unnecessary plastic types (eliminate lever), then scale up a return system (return-based reuse lever), then scale up a refill system (return-based refill lever) and, finally, substitute the remaining materials (substitute lever) to achieve System Transformation targets.

To model the cumulative impacts of all the levers, we take the adjusted mass flows from the eliminate lever and sequentially apply each subsequent lever's percentage changes in demand to the remaining portions. Each resulting mass flow adjustment depends on the previous percentage change being implemented to represent all levers working together comprehensively to achieve their respective targets without overshooting the original demand for single-use plastic. This allows us to identify how much of the overall demand shift is due to the implementation of specific levers.

We employ the following equations to apply the demand shifts sequentially. "Mass" refers to the remaining BAU demand mass flow after applying each lever sequentially. The percentages ("% Demand") represent the relative demand shifts attributed to each lever.

1. $Return\ Mass = Eliminate\ Mass\ \times\ \%\ Return\ Demand$ We calculate the portion of the demand shift attributed to the return lever by multiplying the BAU demand remaining after implementation of the eliminate lever by the relative percentage of demand shifted by the return lever.
2. $Refill\ Mass = (Eliminate\ Mass - Return\ Mass) \times\ \%\ Refill\ Demand$ We estimate the portion of the demand shift attributed to the refill lever based on the remaining mass after accounting for the return lever. We subtract the reduction in BAU demand attributed to the return lever from the BAU demand remaining after implementing the eliminate lever and multiply the result by the relative percentage of demand shifted by the refill lever.
3. $Substitute\ Mass = (Eliminate\ Mass - Return\ Mass - Refill\ Mass) \times\ \%\ Substitute\ Demand$ We model the portion of the demand shift associated with the substitute lever based on the remaining BAU demand after accounting for the return and refill levers. We subtract the remaining mass attributed to the return and refill levers from the portion of BAU demand remaining after the application of the eliminate lever and multiply the result by the relative percentage of demand shifted by the substitute lever.

We use the equations above to calculate the percentage of demand shifted by each lever through using a representative mass of "1" to represent "Eliminate Mass." This allows each

"Return Mass," "Refill Mass" and "Substitute Mass" to be equal to the total percentage demand shift for each lever in System Transformation.

We then distribute these total percentage demand shifts for each lever proportionally by the initial annual percentage shift in demand for each alternative material type based on their totals from the individual lever scenarios. This process ensures that the sequential shifts are applied to the remaining mass after accounting for the previous lever. In doing so, we prevent the overall demand shift across all levers in System Transformation from exceeding the total original BAU demand.

After the sequential application of the upstream packaging levers to obtain an overall reduction in BAU demand, we simultaneously incorporate and apply the collection, recycling and non-packaging levers to represent the downstream flows and their effects on the remaining BAU demand.

We also produce model inputs where all start dates and target years are shifted back five years to analyse the impacts of delayed action.

6.E. Simplification case study

We construct a hypothetical case study to evaluate the potential impacts simplification of plastic could have across the system map.

6.E.1. Material simplification approach

For the purposes of the simplification case study, we focused our modelling on plastic packaging, where we had the greatest product- and polymer-level disaggregation. Under BAU, we evaluate global material flows of 34 different plastic types. In this illustrative case study, we simplify the 34 plastic types based on the packaging product category to four assigned plastic types (see Table 6-25). Beginning in 2025, mass for each plastic type is shifted into the corresponding plastic type (polymer-product category pairing) linearly so that they reach zero by 2040.

Table 6-25. Simplified Plastic Types Based on Packaging Product Category

Packaging product category	Simplified plastic type
PET bottles	PET bottles
Other bottles	Shift to rigid non-food packaging (PP)
Rigid food packaging	Rigid HDPE food packaging
Rigid non-food packaging	Rigid PP non-food packaging
Flexible packaging	Flexible LDPE/LLDPE packaging
Multilayer packaging	Shift to flexible packaging (LDPE/LLDPE)

We then apply a two-stage modelling process. In the first stage, we apply the demand shift based on the approach described above through a Pathways scenario focused on simplification to determine the level of disaggregation of mass flows for each plastic type during the modelling period. To do so, we create matrices for each of the eight geographic archetypes of mass flow by plastic type by year, both for the simplification case study and also for unconstrained BAU as a comparison, to determine the impact of simplification on system behaviours, which is described below.

6.E.2. Impacts of simplification on waste collection, sorting and recycling

To evaluate the impact that simplification has on plastic pollution, we assume that waste collection, sorting and recycling will improve as the number of material types decreases. This is in line with existing research that has demonstrated that many challenges associated with plastic pollution, in particular with successful recycling of plastic, is that there are often too many different chemicals present in plastic feedstock as well as different types of plastic materials and products, which all pose challenges for sorting, cleaning and recycling, in particular.[85] Some of these factors extend beyond what can be reflected in our model, such as specific labelling and product design decisions, though the results of our modelling could hold for those dimensions of material simplification and/or product standardization as well.

In defining the relationship between material simplification and waste management behaviour, we leverage the Herfindahl-Hirschman Index (HHI), which is used in economics to calculate market concentration.

$$HHI_{s,t} = \sum_{i=1}^{n} (WS_i)^2$$

Where:

s is the scenario for which the HHI is being calculated;

t is the year for which the HHI is being calculated; and

WS reflects the proportion of waste generated that is attributable to any given plastic type i.

We then scale the HHI by dividing the simplification case study HHI for each archetype for each year by the corresponding HHI value for BAU. These are then used to adjust the coefficients for the following flows in the system map just for the selected four plastic materials under simplification (thereby assuming BAU behaviour in management of other plastic types):

Increase collection, sorting and recycling output: $Simplification\ Coefficient_t = 1 - \frac{1 - BAU\ Coefficient_t}{HHI\ Ratio_t}$ in each year t

- Flow 10: percentage of waste collected
- Flow 14: percentage of formally collected waste sent for sorting
- Flow 18: percentage of informally collected and sorted waste sent for recycling
- Flow 26: percentage of formally collected and sorted waste sent for recycling that is processed through closed-loop mechanical recycling facilities
- Flow 29: percentage of informally collected and sorted waste sent for recycling that is processed through closed-loop mechanical recycling facilities
- Flow 35: percentage of plastic processed through chemical recycling facilities that is used as feedstock for new polymer production (i.e., P2P)

Decrease losses or fractions moving to unsorted waste: $Simplification\ Coefficient_t = \frac{BAU\ Coefficient_t}{HHI\ Ratio_t}$ in each year t

- Flow 21: percentage of formally sorted waste that is not sent for recycling
- Flow 33: percentage of plastic processed through closed-loop mechanical recycling facilities that is lost
- Flow 34: percentage of plastic processed through open-loop mechanical recycling facilities that is lost
- Flow 37: percentage of plastic processed through chemical recycling facilities that is used as fuel (i.e., P2F)

For both BAU and the simplification case study, we remove capacity constraints across the waste management system, thereby allowing the system to grow collection, sorting and recycling to match the needed amount of plastic mass flow.

The HHI values that are applied in the second-stage Pathways modelling scenario are shown in Table 6-26.

Table 6-26. HHI Values Used in the Simplification Case Study to Adjust Collection, Sorting and Recycling Coefficients

	HI-R		HI-U		LI-R		LI-U		LMI-R		LMI-U		UMI-R		UMI-U	
Year	HHI	HHI ratio	HHI	HHI ratio	HHI	HHI ratio	HHI	HHI ratio	HHI	HHI ratio	HHI	HHI ratio	HHI	HHI ratio	HHI	HHI ratio
2021	1022	1.00	1024	1.00	1158	1.00	1155	1.00	1060	1.00	1007	1.00	970	1.00	992	1.00
2022	1022	1.00	1026	1.00	1158	1.00	1152	1.00	1061	1.00	1007	1.00	970	1.00	991	1.00
2023	1021	1.00	1027	1.00	1157	1.00	1151	1.00	1062	1.00	1009	1.00	970	1.00	990	1.00
2024	1020	1.00	1029	1.00	1158	1.00	1151	1.00	1063	1.00	1011	1.00	969	1.00	989	1.00
2025	1020	1.00	1031	1.00	1158	1.00	1151	1.00	1063	1.00	1013	1.00	968	1.00	988	1.00
2026	1068	1.05	1083	1.05	1184	1.02	1179	1.02	1115	1.05	1061	1.05	1018	1.05	1038	1.05
2027	1130	1.11	1149	1.11	1226	1.06	1223	1.06	1182	1.11	1123	1.11	1081	1.12	1101	1.12
2028	1204	1.18	1226	1.18	1286	1.11	1284	1.12	1262	1.19	1199	1.18	1157	1.20	1177	1.20
2029	1290	1.27	1315	1.27	1362	1.18	1362	1.18	1355	1.27	1289	1.27	1246	1.29	1266	1.29
2030	1387	1.37	1413	1.36	1456	1.26	1458	1.27	1462	1.37	1393	1.37	1348	1.40	1367	1.39
2031	1498	1.48	1524	1.47	1567	1.35	1570	1.36	1581	1.49	1510	1.48	1462	1.51	1481	1.51
2032	1621	1.61	1648	1.60	1696	1.46	1700	1.48	1714	1.61	1640	1.61	1589	1.65	1608	1.64
2033	1757	1.74	1784	1.73	1842	1.59	1848	1.61	1860	1.75	1784	1.75	1729	1.79	1747	1.78
2034	1906	1.90	1933	1.88	2006	1.73	2013	1.75	2019	1.90	1941	1.90	1881	1.95	1899	1.94
2035	2067	2.06	2094	2.04	2188	1.89	2196	1.91	2191	2.06	2111	2.06	2047	2.12	2064	2.11
2036	2238	2.24	2268	2.22	2389	2.06	2397	2.08	2375	2.23	2294	2.24	2224	2.31	2240	2.29
2037	2421	2.43	2455	2.41	2608	2.25	2617	2.27	2572	2.42	2490	2.43	2414	2.51	2430	2.48
2038	2618	2.63	2657	2.61	2846	2.45	2855	2.48	2781	2.62	2699	2.63	2617	2.72	2631	2.69
2039	2827	2.84	2871	2.82	3103	2.67	3112	2.70	3002	2.83	2921	2.85	2831	2.94	2845	2.91
2040	3049	3.07	3098	3.05	3379	2.91	3388	2.94	3236	3.05	3154	3.08	3058	3.18	3070	3.14
2041	3049	3.07	3098	3.05	3379	2.91	3388	2.94	3236	3.05	3154	3.08	3058	3.18	3070	3.14
2042	3049	3.07	3098	3.05	3379	2.91	3388	2.94	3236	3.05	3154	3.08	3058	3.18	3070	3.14

2043	3049	3.07	3098	3.05	3379	2.91	3388	2.94	3236	3.05	3154	3.08	3058	3.18	3070	3.14
2044	3049	3.07	3098	3.05	3379	2.91	3388	2.94	3236	3.05	3154	3.08	3058	3.18	3070	3.14
2045	3049	3.07	3098	3.05	3379	2.91	3388	2.94	3236	3.05	3154	3.08	3058	3.18	3070	3.14

7. Methods for microplastic analysis

As described in section 3.C, Pathways models microplastics flows using source-separate system maps (see Figure 3-2). As with macroplastics, we model BAU and System Transformation for microplastics and generate both System Transformation High and System Transformation Low variations as well as a System Transformation Delay scenario with a five-year delay in the levers.

Across all microplastic types that model the collection of microplastics in wastewater treatment plants (WWTPs), System Transformation High models a 50% reduction in use of WWTP sludge on agricultural lands in HI archetypes. The policy starts in 2025 and is achieved in 2040. This policy is not modelled in System Transformation Low.

7.A. Agricultural microplastics

Agricultural microplastics modelled in BPW2 include those resulting from the degradation of short-term agricultural plastic as well as from the application of compost containing unintentionally-added microplastics (i.e., those present in compost due to accidental disposal of plastic in compost bins). Microplastics from treated WWTP sludge applied to agricultural lands are modelled separately as a component of the other microplastic types. Agricultural microplastics from long-term agricultural plastic, such as greenhouse coverings and irrigation pipes, were not included because of the large variability in their lifespans and the limited data available on degradation rates.

7.A.1. Business as Usual

To estimate the amount of microplastics entering the soil from agricultural plastic, we begin with the mass of short-term agricultural macroplastics (plastic type 49, as shown in Table 3-3). For each archetype, we calculate the annual amount of microplastics entering the soil by applying a degradation rate to the flow of plastic type 49. The degradation rate is the average of two different estimates, which results in an average annual degradation rate of 30%. [86] Due to lack of data, we apply the same degradation rate in all archetypes.

To estimate the amount of microplastics entering agricultural soils from compost, we rely on data from "What a Waste 2.0" on the amount of waste composted by country. [87] We assume all composted waste is applied to agricultural lands. To estimate the amount of microplastics present in compost, we rely on an analysis that found that the average microplastic composition of compost is 0.000215%. [88] Finally, we estimate the distribution of microplastic particles from soil to water via run-off based on estimates in Lwanga et al., 2022, which indicate that 73% of microplastics added to soils eventually enter water via run-off. [89]

7.A.2. System Transformation

System Transformation includes one lever impacting the agricultural microplastics sector. Specifically, System Transformation reflects a ban on intentionally added microplastics in short-term agricultural products. The model assumes that, as a result of this ban, the use of short-term agricultural plastic is reduced by 50%. These assumptions are based on modelling from recent studies. [90]

7.B. Recycling

The scope of the BPW2 modelling of microplastics generated from recycling processes includes microplastic losses to wastewater from washing plastic in preparation for mechanical recycling. It does not include microplastics that may result from other recycling processes, such as dust generated from grinding, or microplastics generated from chemical recycling.

Table 7-1 identifies the key sources used in modelling recycling microplastics.

Table 7-1. Key Sources for Recycling Microplastics Modelling

System map box	Data components	Source	Notes
Macro recycling data	Open-loop and closed-loop recycling inputs and pellets generated from recycling	N/A	Material flow outputs from the macroplastic model
Recycling facilities connected to WWT	Share of recycling facilities connected to WWTP	• Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication.	Assumed to be the same as share of textile production facilities that are connected to WWTP
Microplastics lost in wash water	Rate of microplastic losses to wash water at recycling facilities	**Small-scale facility loss rates:** • Go Suzuki et al., *Mechanical Recycling of Plastic Waste as a Point Source of Microplastic Pollution*, 2022. • Emine Büşra Çolakoğlu and İbrahim Uyanık, *Plastic Waste Management in Recycling Facilities: Intentionally Generated MPs as an Emerging Contaminant*, 2024. • Minh Le Tran et al., *Potential Contamination of Microplastic From Plastic Recycling*	One value applied the same across all archetypes

		Enterprises in Ho Chi Minh City, Vietnam, 2023. **Modern facility loss rates:** • Erina Brown et al., *The Potential for a Plastic Recycling Facility to Release Microplastic Pollution and Possible Filtration Remediation Effectiveness*, 2023. • Johann B. Kasper et al., *Losses and Emissions in Polypropylene Recycling From Household Packaging Waste*, 2025	

7.B.1. Business as Usual

To model the BAU flows of recycling microplastics, we begin with the mass of plastic sent to mechanical recycling in the macroplastic system map (flow 26 + flow 29 for closed-loop and flow 27 + flow 30 for open-loop). We estimated the loss rates from pre-recycling washing based on various studies that measured loss rates for modern and small-scale recycling plants. For the purposes of this analysis, modern recycling facilities represent formal recycling facilities and small-scale recycling facilities represent informal recycling facilities. The loss rate for modern recycling facilities is the average from two sources, yielding a loss rate of 3.1%. The loss rate for small-scale recycling facilities is the average from three sources, yielding a loss rate of 4.1%. We assume that the loss rates do not vary by archetype.

While the macroplastics model estimates how much plastic is collected for recycling by the formal and informal sectors, it does not estimate how much recycling reprocessing is done by each sector. Therefore, we assume the shares represented in Table 7-2 based on expert opinions. The mass of plastic sent to recycling from the macroplastic model for open-loop and closed-loop recycling were multiplied by these shares to determine the mass of plastic reprocessed by each sector in each archetype. Those masses are then multiplied by the loss rates described above to estimate the total mass lost as microplastics to wastewater from mechanical recycling.

Table 7-2. Share of Recycling Reprocessing Performed by Each Sector by Archetype

Archetype	Share of reprocessing done by formal sector	Share of reprocessing done by informal sector

HI	100%	0%
UMI	55%	45%
LMI	30%	70%
LI	0%	100%

Source: Amila Abeynayaka et al., expert panel, Breaking the Plastic Wave 2025, personal communication

We then estimate the amount of plastic lost to solid waste disposal (loss rates from the macroplastic model) to ensure that all losses (macro and micro losses) do not sum to more than the original input mass. The share of recycling facilities connected to wastewater treatment plants was derived from assumptions used in BPW1 (Table 7-3). For a description of updated data for WWTP efficiency and removals, please see section 7.C.

Table 7-3. Share of Recycling Facilities Connected to WWTP by Archetype

Archetype	Share of recycling facilities connected to WWTP
HI	99%
UMI	50%
LMI	50%
LI	50%

Source: Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020

7.B.2. System Transformation

System Transformation includes the increased installation of filters at recycling plants to reduce the amount of microplastics entering wastewater. We estimate that filters reduce microplastic losses to wastewater from the BAU loss rates to 0.25% based on an average of recent studies.[91] In System Transformation High, the HI archetype achieves this reduced loss rate by 2030 and the UMI, LMI and LI archetypes achieve this reduced loss rate by 2040. In System Transformation Low, the HI archetype achieves this reduced loss rate by 2035 and the UMI, LMI and LI achieve this reduced loss rate by 2045.

7.C. Textiles

The scope of the BPW2 modelling of microplastics generated from textiles includes microplastics emitted to wastewater during washing. This includes textile washing during production and at home. The modelling of microplastics emitted by at-home washing includes those from textiles that are already owned, in addition to textiles purchased each year. Importantly, the modelling does not capture microplastics generated due to wearing and/or using textiles – it only captures those associated with washing. Table 7-4 identifies the key sources used in modelling textiles microplastics.

Table 7-4. Key Sources for Textiles Microplastics Modelling

System map box	Data components	Sources	Notes
Synthetic textile production	Total textile production in 2010, 2015, 2020, 2025 and 2030. Compound annual growth rate of total textile production. Share of total textile production that is synthetic textiles.	• Textile Exchange, *Materials Production Dashboard*, 2025.	Described in macroplastic production section.
Synthetic textile production	Share of total production that goes to each income archetype.	• Julien Boucher and Damien Friot, *Primary Microplastics in the Oceans: A Global Evaluation of Sources*, 2017.	Described in macroplastic production section.
Synthetic textile production – microplastics from production	Number of washes per clothing item production.	• Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020.	
Textile washing microplastic production	People per household.	• United Nations Department of Economic and Social Affairs, Population Division, *Household Size and Composition 2018*, 2018.	
Textile washing microplastic production	Wash cycles per household. Share of wash cycles that are handwashing versus machine washing.	• Kirsi Laitala et al., *Laundry Care Regimes: Do the Practices of Keeping Clothes Clean Have Different Environmental Impacts Based on the Fibre Content?* 2020. • Christiane Pakula and Rainer Stamminger, *Electricity and Water Consumption for Laundry Washing by Washing Machine Worldwide*, 2010.	HI archetype estimate as average from 87 data points from two sources; UMI archetype estimate as average from 12 data points from two sources; LMI assume the same as UMI; LI assume no machine washing.

Textile washing microplastic production	Size of loads per household wash.	• Christiane Pakula and Rainer Stamminger, *Electricity and Water Consumption for Laundry Washing by Washing Machine Worldwide*, 2010.	HI archetype estimate as average from 6 data points; UMI archetype estimate as average from 3 data points from two sources; LMI and LI assume the same as China.
Textile washing microplastic production	Losses from machine washing and handwashing.	• Francisco Belzagui et al., *Microplastics' Emissions: Microfibers' Detachment From Textile Garments*, 2019. • Francesca De Falco et al., *Evaluation of Microplastic Release Caused by Textile Washing Processes of Synthetic Fabrics*, 2018. • Edgar Hernandez, Bernd Nowack, and Denise M. Mitrano, *Polyester Textiles as a Source of Microplastics From Households: A Mechanistic Study to Understand Microfiber Release During Washing*, 2017. • Niko L. Hartline et al., *Microfiber Masses Recovered from Conventional Machine Washing of New or Aged Garments*, 2016. • U. Pirc et al., *Emissions of Microplastic Fibers From Microfiber Fleece During Domestic Washing*, 2016.	

Microplastics from production	Share of production (industrial) facilities connected to wastewater treatment plants. Fate of microplastics after removal from industrial wastewater treatment.	• Expert panel assumptions.	Assumed that all microplastics removed during industrial wastewater treatment are sent to engineered landfills.
Microplastics from production	Share of MP removed from wastewater from production wastewater treatment.	• Mohan Seneviratne, *Wastewater Treatment Technologies*, 2018.	Equal to removal from primary WWT (updated from BPW1). We also assumed that textile production facilities are connected to WWTPs at the same rate by archetype as recycling facilities.
Microplastic fibre weight	Convert from number of microplastic fibres to weight of microplastics.	• Jianli Liu et al., *Microfiber Pollution in the Earth System*, 2022.	
Microplastics directly entering soil	Microplastics losses to soil from handwashing.	• Expert panel assumptions.	

7.C.1. Business as Usual

To estimate microplastics generated from textiles during washing, we begin with the estimated mass of synthetic textiles produced annually. This estimate comes from the microplastic model (plastic type 47). We then estimate the amount of microfibres lost during washing in the production phase using the methods used in BPW1.[92] We also use the BPW1 methods to estimate the amount of synthetic textiles washed annually by end users.

For all microplastic sources that enter wastewater treatment plants, we update the data from BPW1 with data from Quantis and EA – Earth Action (EA), 2020.[93] This updates the share of households connected to WWTPs by archetype and the effectiveness of each level wastewater treatment (primary, secondary, tertiary). We rely on BPW1 data for the distribution of captured microplastics to terrestrial pollution, dumpsites, landfills and incineration.

7.C.2. System Transformation

Table 7-5 describes the policy levers applied to the textiles sector in System Transformation, which include both upstream and downstream levers to reduce microplastic emissions from the washing of textiles.

Table 7-5. Policy Levers Applied in System Transformation to the Textiles Sector

Upstream or downstream	Lever name	Summary of modelling approach
Upstream	Reduce use	Reduce demand for synthetic textiles by 16% in System Transformation Low and by 32% in System Transformation High in the HI archetype. Reduce demand for synthetic textiles by 12% in System Transformation Low and by 24% in System Transformation High in all other income archetypes. Reductions begin in 2025 and are achieved by 2040 in all archetypes. These assumptions are based on modelling from recent studies.
Upstream	Improve product design	Reduce shedding rates during industrial, machine and handwashing by 72% by 2030 in System Transformation High and by 2040 in System Transformation Low in all archetypes. These modelling assumptions are based on the BPW1 analysis.
Downstream	Improve capture	Increase capture rate of filters in production facilities and home washing machines to 78% by 2035 in System Transformation High and by 2040 in System Transformation Low in all archetypes. Assume only 50% of home washing machine users dispose of captured fibres properly.
Downstream	Improve capture	Reduce the amount of household wastewater that is uncollected in the BAU by 50% from 2025 to 2040 in all archetypes.

Sources: Systemiq, *Towards Ending Plastic Pollution by 2040: 15 Global Policy Interventions for Systems Change*, 2023. Winnie W. Y. Lau et al., *Evaluating Scenarios Toward Zero Plastic Pollution*, 2020. Imogen E. Napper, Aaron C. Barrett, and Richard C. Thompson, *The Efficiency of Devices Intended to Reduce Microfibre Release During Clothes Washing*, 2020

7.D. Personal care products

BPW2 includes modelled microplastics from two types of personal care products (wash-off and stay-on), which differ mainly in their management pathways. Microplastics generated from wash-off personal care products enter the environment through water, while microplastics from stay-on products can eventually be washed off and enter the water, but may also be disposed of via solid waste systems (e.g., when removed via cotton balls and disposed of in MSW).

7.D.1. Business as Usual

BPW2 followed the same approach taken in BPW1 to model microplastics generated from personal care products, but incorporates the updated WWTP connection modelling, as described in section 7.C.[94]

7.D.2. System Transformation

Table 7-6 describes the policy levers applied to the personal care products sector in System Transformation, which include both an upstream and a downstream lever to reduce microplastic emissions from personal care products.

Table 7-6. Policy Levers Applied in System Transformation to the Personal Care Products Sector

Upstream or downstream	Lever name	Summary of modelling approach
Upstream	Ban or reduce use	In System Transformation High, ban intentionally added microplastics in wash-off personal care products (PCPs) and ban or significantly reduce them in leave-on PCPs. The bans in wash-off products begin in 2025 for the high-income archetype and in 2035 for all other archetypes. The bans or reductions for leave-on products begin in 2030, with bans occurring in high-income archetypes and reductions of 50% occurring in all other archetypes. In System Transformation Low, reduce intentionally added microplastics in wash-off PCPs by 95% and by 30% in leave-on PCPs by 2040 in all archetypes.
Downstream	Improve capture	Reduce the amount of household wastewater that is uncollected in the BAU by 50% from 2025 to 2040 in all archetypes.

7.E. Tyres

BPW2 models microplastics generated from tyre wear from five types of tyres: passenger vehicles, motorbikes, light-duty vehicles, heavy-duty vehicles and airplanes. The model includes the shedding rate for these tyres traveling on roads, highways and runways. The model contains assumptions about the shedding rates (mg of plastic shed per km) for each tyre type.

7.E.1. Business as Usual

The modelling of BAU for tyre-related microplastics follows the same approach as BPW1 with the exception of updated flight data to estimate microplastic losses occurring from tyre shedding on runways. For this update, we relied on flight data from World Bank, 2021 (data from 2011 to 2021) and used growth from 2011 to 2019 to estimate the rate of future growth in departures from countries for 2021 to 2040 (excluded 2020 data due to pandemic).[95] We then aggregated departure flight data to the archetype level.

7.E.2. System Transformation

Table 7-7 describes the policy levers applied to the tyres sector in System Transformation, which include both upstream and downstream levers to reduce microplastic emissions from tyres.

Table 7-7. Policy Levers Applied in System Transformation to the Tyres Sector

Upstream or downstream	Lever name	Summary of modelling approach
Upstream	Improve product design	Based on EU abrasion limits for tyre particle emissions, the model estimates reduction in the loss rate per kilometre driven by 10% in System Transformation Low and 30% in System Transformation High for all archetypes. The high-income archetype achieves targets between 2032 and 2036, and all other archetypes achieve targets by 2034 and 2038.
Upstream	Reduce use	Reduce per capita kilometres driven by 50% for the high-income archetype and by 20% for all other archetypes. The reduction begins in 2025 and is achieved in all archetypes by 2040. These modelling assumptions are based on the BPW1 analysis.
Downstream	Improve capture	For all non-HI urban archetypes, increase installation of sustainable drainage systems to improve capture of microplastics from roadways. The capture rate is increased to the same levels as in the high-income urban archetype. These modelling assumptions are based on the BPW1 analysis.

Source: European Commission, *Tyres*

7.F. Paint

BPW2 models microplastics generated from paint losses during application (e.g., through overspray), wear and tear (e.g., through abrasion) and removal. It includes losses from six types of paints: architectural, automotive, general industrial, industrial wood, marine coatings and road markings.

7.F.1. Business as Usual

Our approach to modelling microplastics generated from paint builds on detailed existing data and methods led by EA, which evaluated market reports to determine demand for paint across sectors in 2019.[96] With a focus on paints that shed microplastics during application, wear and tear, and removal, we aggregated the data provided by EA to the BPW2 archetypes and applied their modelling assumptions on the rate of microplastic generation and release to air, water and wastewater treatment. EA did not include modelling for sustainable drainage systems (SUDs), but did include modelling to road run-off. For microplastics lost on the road, we used data from microplastics shed from tyres to split the proportion that gets captured in SUDs. For wastewater treatment, we used the same percentages that are used for the other microplastic types (i.e., treatment is the same across all microplastic types).

7.F.2. System Transformation

Table 7-8 describes the policy levers applied to the paint sector in System Transformation, which include both upstream and downstream levers to reduce microplastic emissions from paint.

Table 7-8. Policy Levers Applied in System Transformation to the Paint Sector

Upstream or downstream	Lever name	Summary of modelling approach
Upstream	Improve product design	Reduce the loss from overspray during paint application in the HI archetype for the following paint types: general industrial (33%), automotive (20%), industrial wood (15%). Reduce the loss of general industrial paint by 14% in the HI and UMI archetypes. Reductions begin in 2025 and are achieved by 2040 in System Transformation High and begin in 2030 and are achieved by 2045 in System Transformation Low.
Upstream	Implement protection methods	Reduce the loss of road markings by 20% in all archetypes. Reduce the loss of marine paint in the recreation sector by 5% in the HI archetype. Reductions begin in 2025 and are achieved by 2040 in System Transformation High and begin in 2030 and are achieved by 2045 in System Transformation Low.
Upstream	Reduce use	Reduce the use of interior and exterior concrete paint by 50% in the HI and UMI archetypes. Reductions begin in 2025 and are achieved by 2040 in System Transformation High and begin in 2030 and are achieved by 2045 in System Transformation Low.
Downstream	Improve capture	Reduce the loss of marine paint from the commercial sector during dry docking by 95% in HI and UMI archetypes. For marine, auto and road markings, increase installation of SUDS in HI by 65%, increase installation of SUDS in other archetypes to 5%. Changes begin in 2025 and are achieved by 2040 in System Transformation High and begin in 2030 and are achieved by 2045 in System Transformation Low.

7.G. Pellets

BPW2 models microplastics from pellets that are mishandled during sea transport and at recycling and production facilities, resulting in spills and losses. The modelling does not include pellets lost during land transport.

7.G.1. Business as Usual

To model microplastics from pellets in the BAU, we begin with the mass of exported polymers (flow 1 from the macroplastic model) to estimate the mass of plastic transported at sea. Flows 2 and 3 from the macroplastic model are summed to represent the mass of plastic pellets handled by pellet handlers. Flows 26, 27, 29 and 30 are summed to estimate the mass of pellets handled at recycling facilities. We then apply the same methods used in BPW1 to these input values to estimate the mass flow of plastic pellet microplastic particles.[97]

7.G.2. System Transformation

System Transformation introduces upstream-focused policy levers to prevent pellet loss through spills and mishandling during production, recycling and transportation of pellets. System Transformation achieves a 95% reduction in pellet loss, based on previous studies quantifying the impacts of regulation requiring the full supply chain to be certified or to comply with standards regarding best practice measures to prevent pellet loss.[98] In 2025, 32% of all pellets produced are shipped internationally. Under System Transformation, sea transport losses (e.g., during spills) are reduced by 95% starting in 2030 in all archetypes. Losses also occur at production and recycling facilities when the pellets are being stored. These losses could be reduced by 95% from 2025 to 2040 in all archetypes if uptake of best practices, monitoring and reporting is increased in production and recycling facilities.

7.H. Modelling limitations for microplastics

Under the current modelling framework, we do not explicitly account for the mass loss associated with microplastics in the macroplastic mass flow modelling. Therefore, reported end-of-life figures could result in duplication of some plastic mass (i.e., mass of plastic tyres that are modelled as being landfilled could also be reflected in some of the mass moving in the microplastic model). We are working towards a version of Pathways that can explicitly link the macro- and microplastic modelling frameworks and run them in parallel, which would allow us to account for slight plastic mass losses from macroplastic waste that result from shedding of microplastic particles.

8. Estimating externalities

Externalities occur when one person's or firm's actions affect the well-being of a third party and that effect is not reflected in the market price of the good or service involved. Because the market price of goods and services doesn't reflect the (higher) full social cost of the consumption decisions, consumers and producers tend to overconsume these goods and services, with third parties not appropriately compensated for the damages. Internalizing the negative externalities of plastic use – including environmental pollution, GHG emissions and human disease – is a way to incentivize more efficient and equitable decisions that account for societal costs.

Externalities are distributed across the plastic life cycle – from production, to use and to ultimate disposal and management (or mismanagement), though a substantial share are associated with the production stage.[99]

For this study, we estimate the externalities from GHG emissions, focusing on the primary plastic production stage (from feedstock extraction through product shaping). The GHG emissions which drive these externality estimates are, in principle, discoverable, and they can be linked to specific types of plastic and to different production methods. For GHGs, the externality per unit of pollutant (e.g., climate change impacts per metric ton CO_2) is relatively uniform regardless of where the emission occurs. The same is not necessarily true of emissions of non-GHG air pollutants for which health-related externalities depend on population exposure and are expected to vary with location.

Our estimates of the GHG emissions from producing different virgin polymers, as well as those from their conversion, indicate that producing one metric ton of virgin polymers generates emissions ranging between 3.5 and 5.7 metric tons CO_2e depending on polymer, with figures rising to 4.5 to 6.5 metric tons CO_2e once product conversion is included. In this analysis, we also compare the production and conversion of primary plastic with the recycling of plastic and its conversion into end-products. For the latter, we use estimated emissions for acquiring secondary materials through plastic recycling and add to these emissions the same figures for conversion as are used for the primary plastic (but without the upstream stages relevant only to virgin plastic production).

To monetize GHG externalities, we use values of the externalities related to CO_2 emissions from two sources. The sources offer recent estimates derived using each of the two main approaches commonly used to evaluate the effects of policies affecting GHG emissions: a social cost approach and an abatement/mitigation cost approach.

1. The first source – U.S. EPA, 2023 – estimated the social costs of CO_2, methane and nitrous oxide based on the monetary value of the net harm to society from emitting a metric ton of each GHG into the atmosphere in a given year.[100] In theory, this is comprehensive metric that includes the value of all future climate change impacts (both negative and positive), including changes in net agricultural productivity, human health effects, property damage from increased flood risk, changes in the frequency and severity of natural disasters, disruption of energy systems, risk of conflict, environmental migration and the value of ecosystem services. The U.S. EPA study presents values under different near-term Ramsey discount rates and for emission years out to 2080. Discounting more heavily leads to lower values, and emissions in later years are linked to higher social costs.[101]
2. The second source – U.K. Department for Energy Security and Net Zero (U.K. DESNZ), 2023 – adopts a "target consistent" approach in which estimates are made of the marginal abatement cost of the U.K. meeting its commitments to reduce GHG emissions.[102] A review study in 2021 confirmed this as the approach that should be preferred in the U.K., given that the U.K. has committed itself to defined carbon budgets in future.[103] There is considerable uncertainty around the abatement costs, both currently and even more so regarding a pathway consistent with the U.K. meeting its obligations. The U.K. DESNZ approach presents low, central and high figures, these represented by "a plus or minus 50% sensitivity range has been deemed appropriate around the central series."[104]

The former source provides an up-to-date estimate from the social cost perspective which was subject to extensive peer review, and the latter source provides a regularly updated estimate from the abatement cost approach from a jurisdiction whose commitments are relatively progressive (albeit that were all nations to follow the same trajectory, the likelihood of remaining consistent with a 1.5 degree trajectory is diminishingly small). While not directly comparable due to the differences in methodological perspectives, the two sources nonetheless provide estimates that show an interesting overlap, with the U.S. EPA social costs for the higher discount rates being similar to the U.K. DESNZ low and central marginal abatement costs.

For this analysis, we use averages of values from the two sources. The low, central and high U.K. DESNZ values are paired with the U.S. EPA social costs derived using, respectively, discount rates of 2.5%, 2% and 1.5% to estimate low, central and high values.[105] We quantify the resulting externalities, expressed in 2021 US$, based on U.S. EPA (2023) and U.K. DESNZ (2023).[106] (See Table 8-1.)

Table 8-1. Average Values and Derivation of Figures for Between 2030 and 2040

Based on average of values, expressed in 2021 US$, of externalities per metric ton CO_2

Year	Low	Medium	High
2030	$169.25	$312.36	$486.84
2031	$172.18	$317.24	$493.67
2032	$175.15	$322.19	$500.61
2033	$178.17	$327.22	$507.64
2034	$181.23	$332.32	$514.79

2035	$184.34	$337.51	$522.04
2036	$187.50	$342.77	$529.41
2037	$190.70	$348.11	$536.88
2038	$193.95	$353.53	$544.47
2039	$197.26	$359.03	$552.18
2040	$200.61	$364.62	$560.00

Source: United Kingdom Department for Energy Security and Net Zero, *Green Book Supplementary Guidance: Data Tables 1 to 19*, Nov. 30, 2023. United States Environmental Protection Agency, *EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*, 2023

We treat the totality of the CO_2 equivalent emissions as though they were all CO_2.[107] This is a simplification; U.S. EPA provides GHG-specific social costs that could be applied to methane emissions, for example, but the UK study includes no specific abatement costs for GHGs other than CO_2. The results are shown in Table 8-2.

Table 8-2. Externalities From GHG Emissions From Polymer Production and Conversion Using Virgin Material and Mechanically Recycled Plastics

By polymer, in 2021 US$ per metric ton

Polymer production and conversion using virgin material						
	2030			**2040**		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
LDPE/LLDPE	800	1,476	2,301	948	1,723	2,646
HDPE	795	1,467	2,286	942	1,712	2,629
PP	758	1,398	2,179	898	1,632	2,507
PVC	807	1,490	2,322	957	1,739	2,671
PS	1,084	2,000	3,117	1,284	2,335	3,586
PET	1,097	2,024	3,155	1,300	2,363	3,629
PET bottles	1,097	2,024	3,155	1,300	2,363	3,629
Other	923	1,703	2,654	1,094	1,988	3,053
Polymer production and conversion from mechanical recycling						
	2030			**2040**		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
LDPE/LLDPE	238	439	683	282	512	786
HDPE	265	489	762	314	571	876
PP	245	452	704	290	527	809
PVC	250	461	718	296	538	826
PS	227	419	653	269	489	751
PET	281	519	808	333	605	930
PET bottles	228	420	655	270	491	754
Other	195	360	561	231	420	645

Were these GHG externalities to be fully internalized for plastic alone, the market would likely see a drop in overall demand for plastic (both own- and cross-price effects) with an increased share of the ongoing use being taken up by secondary materials: It would not be unreasonable to expect an increased interest in design of packages and products to ensure that a greater share of what becomes waste can be used in high-quality recycling (where the secondary material substitutes for primary plastic use). These effects would be enhanced were other externalities, such as air pollution, to be factored into the analysis. [108]

The situation would be somewhat different in the case where a policy instrument internalizes externalities for all materials. Cross-price effects would be less pronounced, and demand for all materials would be affected (including those which might be considered as substitutes for plastic). That might result in the demand for plastic as a whole falling by less than in the case where the instrument targets plastic alone. The same effect, in terms of increasing shares of ongoing demand being met by secondary materials, would be observed (as well as, potentially, for other materials). This is a more economically efficient approach and likely reduces the extent of burden-shifting that may result from a focus on plastic alone.

As an example of how such an approach might influence decisions regarding reuse, we consider the GHG emissions and associated externalities from return business models and compare these with those of virgin plastic production. We evaluate substitution in specific product categories, such as rigid food packaging and flexible packaging to isolate comparisons for individual polymers, as rigid food packaging is typically HDPE or PP, whereas flexible packaging is predominantly LDPE. We then apply the reuse material production requirements (e.g., weight ratios, use of existing containers) and assumptions on the number of use cycles to derive material demand externality estimates to compare with virgin plastic production.

The results, which incorporate the GHG emissions associated with production of the substitute materials used in return systems (plastic, glass and metal), indicate that the GHG-related externalities associated with material production to enable return systems are consistently lower than those from virgin plastic production. The results indicate that under a measure that seeks to internalize the GHG externalities, return would benefit substantially relative to virgin plastic use. It would be reasonable to expect increased interest in return models as a way to switch away from single-use of virgin plastic (and other materials). GHG emissions associated with the return system (washing, transportation, etc.) are also a meaningful consideration, as seen in Table 8-3.

Table 8-3. GHG Emissions and Externalities From GHG Emissions From Return-Based Reuse Systems by Material Type

In 2021 US$ per ton of CO_2e associated with the mass of return material needed to displace one ton of single-use plastic

Plastic return						
	2030			**2040**		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
PET beverage bottles	158	292	454	187	340	523
Other bottles	157	290	452	186	339	520
Rigid food packaging (not bottles)	149	276	430	177	322	494
Rigid non-food packaging (not bottles)	149	276	430	177	322	494
Flexible packaging	373	689	1,074	443	804	1,236
Multilayer packaging	373	689	1,074	443	804	1,236
Glass return						
	2030			**2040**		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
PET beverage bottles	360	665	1,036	427	776	1,192
Other bottles	360	665	1,036	427	776	1,192
Rigid food packaging (not bottles)	97	179	279	115	209	321

Rigid non-food packaging (not bottles)	97	179	279	115	209	321
Flexible packaging	93	172	268	110	200	308
Multilayer packaging	93	172	268	110	200	308
Metal return						
	2030			**2040**		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
PET beverage bottles	493	909	1,417	584	1,061	1,630
Other bottles	493	909	1,417	584	1,061	1,630
Rigid food packaging (not bottles)	369	681	1,061	437	795	1,220
Rigid non-food packaging (not bottles)	369	681	1,061	437	795	1,220
Flexible packaging	369	681	1,061	437	795	1,220
Multilayer packaging	369	681	1,061	437	795	1,220

9. Case study on health impacts from chemicals in plastic products

This section was supported by Megan Deeney, Lei Huang and Peter Fantke and provides more detail on the modelling approach and results of the analysis of use-related impacts from plastic that are discussed briefly in BPW2.[109]

Over 16,000 chemicals have been identified in plastic, which can vary substantially among different polymer types and different product applications.[110] These chemicals, henceforth referred to as "plastics chemicals," include: (1) monomers; (2) processing aids; (3) additives that give plastic form, functionality and aesthetics such as plasticizers (providing plastic flexibility), antioxidants and colourants, or fulfil other functions; and (4) non-intentionally added substances (NIAS) including impurities, reaction by-products and degradation products.[111]

9.A. Background

Bisphenols, chlorinated and brominated flame retardants, per- and polyfluoroalkyl substances, and phthalates in plastic have been estimated to cause 33 million DALYs per year worldwide, or between US$250 billion and US$675 billion in health costs per year in the United States and more than US$1.5 trillion globally.[112] These estimates were based a subset of highly hazardous chemicals for which we have strong data linking them to leading global burden of disease outcomes. While these may be among the most harmful of plastic chemicals, they represent a small proportion of all chemicals found in plastic and their association with only certain diseases in up to two-thirds of the global population. The true scale of plastic chemical impacts on human health is therefore likely to be higher still.

Many scientific methods exist for assessing the health impacts of chemicals, each offering critical insights and each with its own challenges. Toxicology, epidemiology and novel computational research methods have been instrumental in identifying chemical hazards and their effects on human health, but with thousands of chemicals in plastic, many data gaps remain. Limitations include that studies may often consider only select chemicals under certain conditions, difficulties of translating in vitro to in vivo effects, the cost, resources and ethical considerations of conducting research, particularly for studies in humans, long latency periods of associated diseases such as cancers, and how to account for multiple sources and different routes of exposure to chemicals in the real world.

LCA has developed methods to account for the health impacts of chemicals released across plastic life cycles. However, traditional LCA tends to not yet account for health effects associated with exposure to chemicals inside plastic during the use stage of plastic products, which often dominate overall human exposure to toxic chemicals along plastic product life cycles.[113] Holistic assessments combining strengths of different methodologies in a consistent framework are essential for addressing the complex and evolving landscape comprising thousands of chemicals in plastic.

USEtox is a global reference model for assessing the human health impacts of chemicals in LCA, formally endorsed by the Life Cycle Initiative since 2013.[114] It combines insights from chemistry, environmental science, toxicology and physics and can be used to estimate the human toxicity impacts of chemicals identified or known to be used in plastic and released along plastic life cycles, accounting for cancer, reproductive/developmental toxicity and chronic general non-cancer toxicity effects as main health effect categories (see the Methods Annex).

Based on a given concentration of a chemical in a product (its weight fraction), USEtox models (1) its transfer out of the plastic and its near-field and far-field dispersal; (2) the quantity to which humans are subsequently exposed, considering both the user of the plastic and the broader population exposed through environmental chemical dispersal; (3) human uptake of the chemical through ingestion, dermal and oral exposure routes; and (4) the effects associated with chemical uptake including cancer, reproductive/developmental and general non-cancer effects. Finally, incidence cases of cancer as well as reproductive/developmental and general non-cancer incidence cases are translated to DALYs through severity factors of 11.5 DALYs per incidence case of cancer, 44.1 for reproductive/developmental effects and 2.4 for general non-cancer cases.[115] One DALY represents one year of healthy life lost through premature death and/or life lived with disease or disability. One year can thus be converted to equivalent minutes, hours and seconds.

9.B. Case study: Plastic doll

9.B.1. Chemical composition

Based on Aurisano et al., 2022, we have weight fraction data for 71 chemicals in soft PVC plastic toys, mostly relating to plasticizers and fragrances (Table 9-1).[116] Only plasticizers were found at weight fractions exceeding 0.1% of the plastic, suggesting these are intentionally added substances, while other chemicals are likely to be NIAS.

Of the chemicals identified in Aurisano et al., 2022, for soft PVC toys, 15 were associated with having potential carcinogenic effects and 62 with reproductive or developmental non-carcinogenic effects in USEtox.[117]

Table 9-1. Chemical Weight Fraction Data for Soft PVC Toys

Row labels	Count of chemicals
Plasticizer	19
Fragrance	15
Flame retardant	8
Unknown function	7
Ubiquitous	6
Antioxidant	2
Solvent	2
Flame retardant (and plasticizers)	2
Emollient	2
Viscosity control agent	1
Catalyst	1
Surfactant	1
Perfumer	1

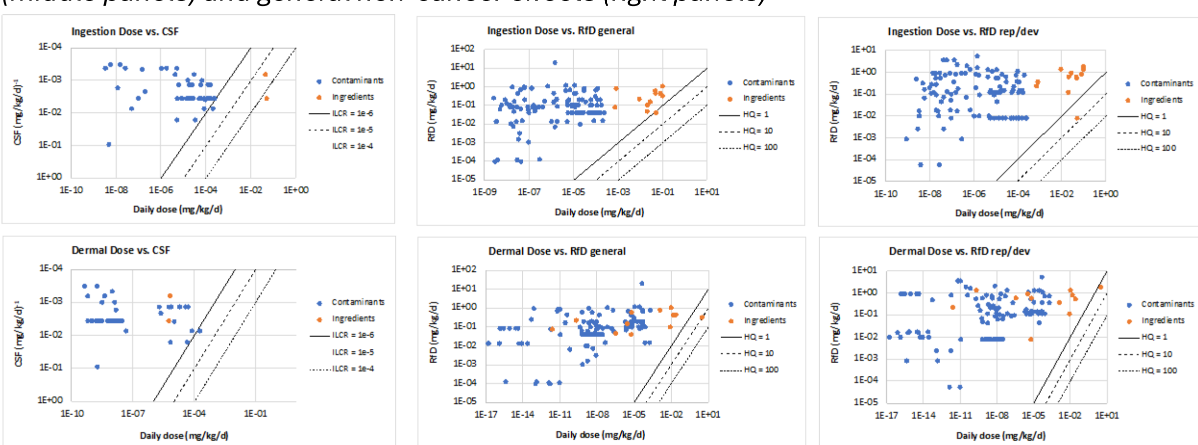
Row labels	Count of chemicals
UV absorber	1
Colorant	1
Monomer	1
Metabolite	1
Total	71

The most problematic for cancer effects (based on product-specific release, resulting exposure and relative chemical toxicity) per unit mass of chemical in the doll is the colourant naphthalene, and the most problematic for non-cancer (particularly for reproductive/developmental effects) is 2,2'4,4'-tetrabromodiphenyl ether (PBDE-47), a well-known hazardous flame retardant estimated to cost US$158 billion in health costs in the U.S., based on its use in plastic alone.[118]

While most chemical exposure doses from the PVC doll were below those considered to present unacceptable risk to the general population, two intentionally added flame retardants and one plasticizer (at less than 0.1% weight fraction indicating NIAS) exceeded acceptable cancer risk factors (generally considered to be risks higher than 1 in 1,000,000 for the general population) for the ingestion route, and one flame retardant exceeded the acceptable hazard quotient for reproductive/developmental, and general non-cancer effects (generally considered to be a hazard quotient higher than one) for both ingestion and dermal contact routes (Figure 9-1).

Figure 9-1. Human Exposure Dose of Chemicals From PVC Dolls

Relative to cancer risk factors (left panels) and to hazard quotients for reproductive/developmental (middle panels) and general non-cancer effects (right panels)



Note: For cancer, a risk of >1 x 10^{6} is considered unacceptable for the general population and 1 x 10^{4} for workers. For non-cancer (including reproductive and developmental effects), a hazard quotient of >1 is considered unacceptable for the general population.

9.B.2. Scenario: Hypothetical single doll

Using Aurisano et al., 2022, data on chemicals contained in soft plastic material-based toys, the complete chemical composition of a PVC doll was constructed.[119] This includes only the polymer and one intentionally added chemical for each relevant function (Table 9-2). We created two versions of the doll, one that contains the chemicals with the lowest human health impact (based on release, resulting exposure and relative toxicity) per unit mass of chemical in the doll for each function (MIN), and one that contains those with the greatest impact by function (MAX), for all chemical functions where we had more than one possible chemical available. The scenario imagines that the doll is played with by a child 2 to 3 years of age for one year, holding it for 12.6 minutes per hour and mouthing it for three minutes per day. The scenario accounts for all relevant exposure-uptake pathways including ingestion, dermal and inhalation of chemicals.

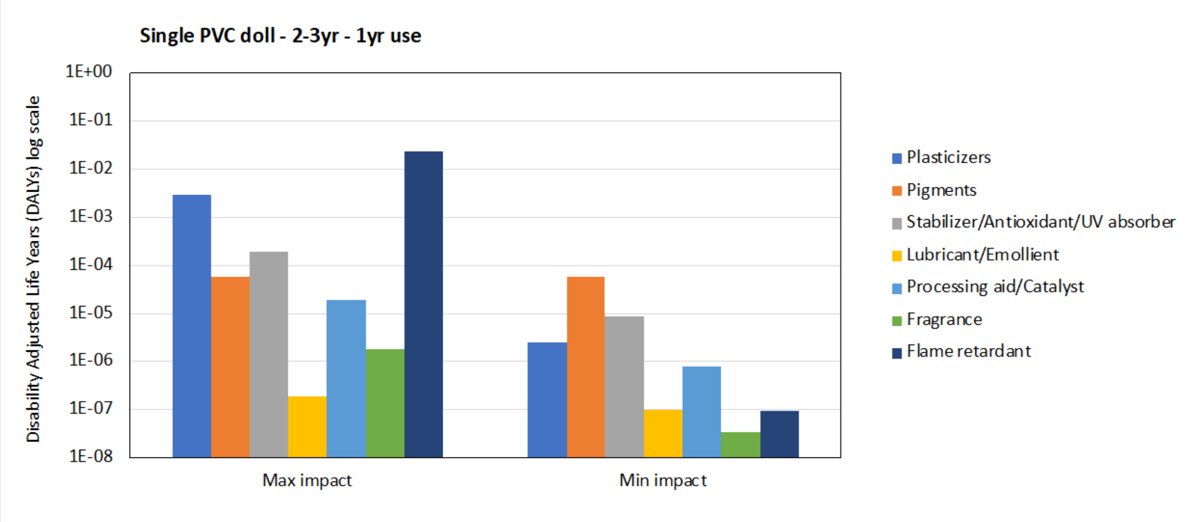
Table 9-2. Chemical Composition of a Soft PVC Doll

Chemical component	Weight fraction
PVC	0.500
Plasticizers	0.250
Fillers	0.200
Pigments/Colorants	0.010
Stabilizers/antioxidants/UV absorbers	0.010
Lubricants/emollients	0.005
Processing aids/catalysts	0.005
Fragrances/perfumers	0.010
Flame retardants	0.010
Total	**1.000**

Between 36 minutes and 10 days of healthy life lost based on MIN impact and MAX impact versions of the single doll, mostly due to the different impacts of the flame retardant (Figure 9-2). Removing the pigment completely would reduce the overall healthy life lost to between six minutes and 10 days for the remaining chemical components, and removing the pigment plus the flame retardant would reduce this to between six minutes and one day of healthy life lost (Figure 9-2).

Figure 9-2. MIN and MAX Impact of a Theoretical Soft PVC Doll

Based on the least and most toxic chemicals for each function within the soft plastic material

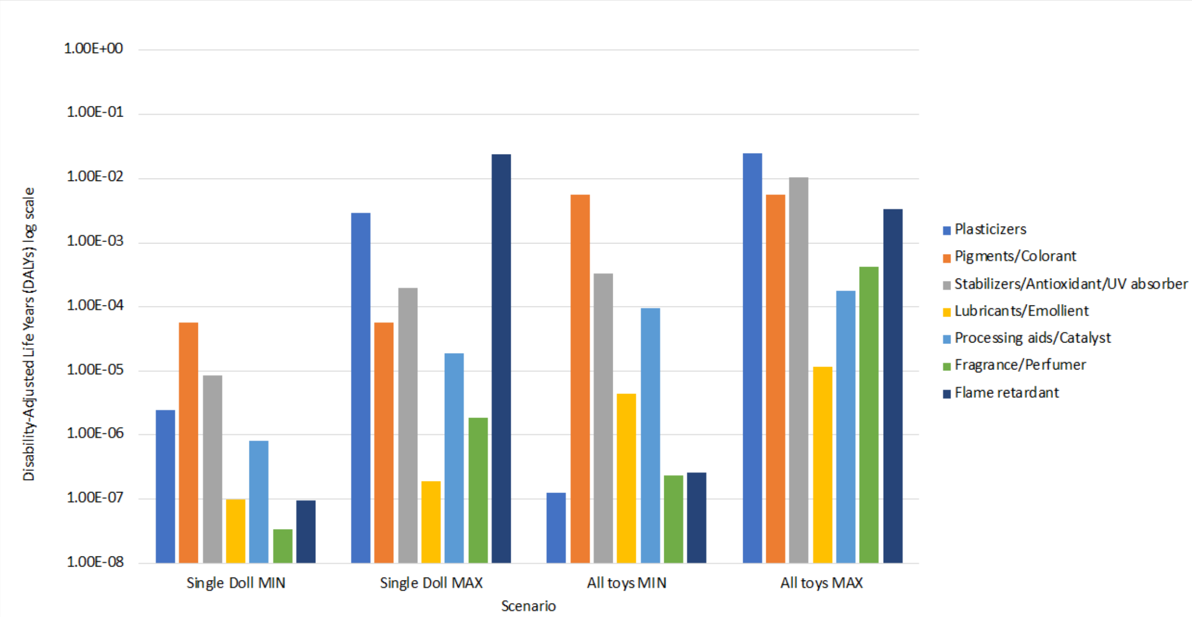


9.B.3. Scenario: Scaling up to a household

It is important to consider that children, and their households, will likely have more than one plastic toy. Here, we scale up the scenario of the single children's doll to reflect an estimated average of 54 kg of plastic toys found in a child's room. [120] The child's chemical exposure in this scenario comes from inhalation and dermal uptake of volatile and semi-volatile chemicals from the toys in the room.

- Between two and 16 days of healthy life lost in the MIN and MAX impact scenarios.
- In the MAX scenario the plasticizer and the stabilizer/antioxidant/UV absorber contributed most to overall DALYs; in the MIN scenario, the pigments/colourants contributed most, followed by the stabilizer/antioxidant.
- Removing the pigment altogether resulted in between four hours and 14 days of healthy life lost in the MIN and MAX scenarios for remaining chemicals.
- Removing both the pigment and the flame retardant resulted in between four hours and 13 days of healthy life lost in the MIN and MAX scenarios for remaining chemicals.
- Relative to the total impacts from the single doll scenario, the total impacts from all toys were two order of magnitude higher comparing the MIN scenarios of each, and 65% higher comparing the MAX scenarios of each.

Figure 9-3. DALYs Associated With Functional Chemicals in the Hypothetical Single PVC Doll Scenario Versus the Scaled-Up Scenario That Considers All Toys in a Child's Room



Note: We assessed four scenarios as shown: (1) a single doll containing the minimum impact chemicals by function (single doll MIN); (2) a single doll containing the maximum impact chemicals by function (single doll MAX); (3) all toys in a child's room containing the minimum impact chemicals by function (all toys MIN); and (4) all toys in a child's room containing the maximum impact chemicals by function (all toys MAX).

Finally, to assess the total impacts on the child, we sum the single doll impacts with the impacts from all toys (Figure 9-4). The child's chemical exposure now comes from touching and mouthing one toy at a time, also during one year in which one toy is held for 12.6 minutes per hour and mouthed for three minutes per day, combined with inhalation and dermal uptake of volatile and semi-volatile chemicals from this doll and also from all the other toys in the room. The summary of DALYs from each scenario and the combined impacts is provided in Table 9-3.

- Between two and 26 days of healthy life lost in the combined MIN and MAX impact scenarios from both the single toy and all toy scenarios.
- In the MAX scenario the plasticizer and the flame retardant contributed most to overall DALYs; in the MIN scenario, the pigments/colourants contributed most, followed by the stabilizer/antioxidant.
- Removing the pigment altogether resulted in between four hours and 24 days of healthy life lost in the MIN and MAX scenarios for remaining chemicals.
- Removing both the pigment and the flame retardant resulted in between four hours and 14 days of healthy life lost in the MIN and MAX scenarios for remaining chemicals.

Figure 9-4. DALYs Associated With Functional Chemicals From the Combined Exposure to the Single Doll and All Toys in the Room

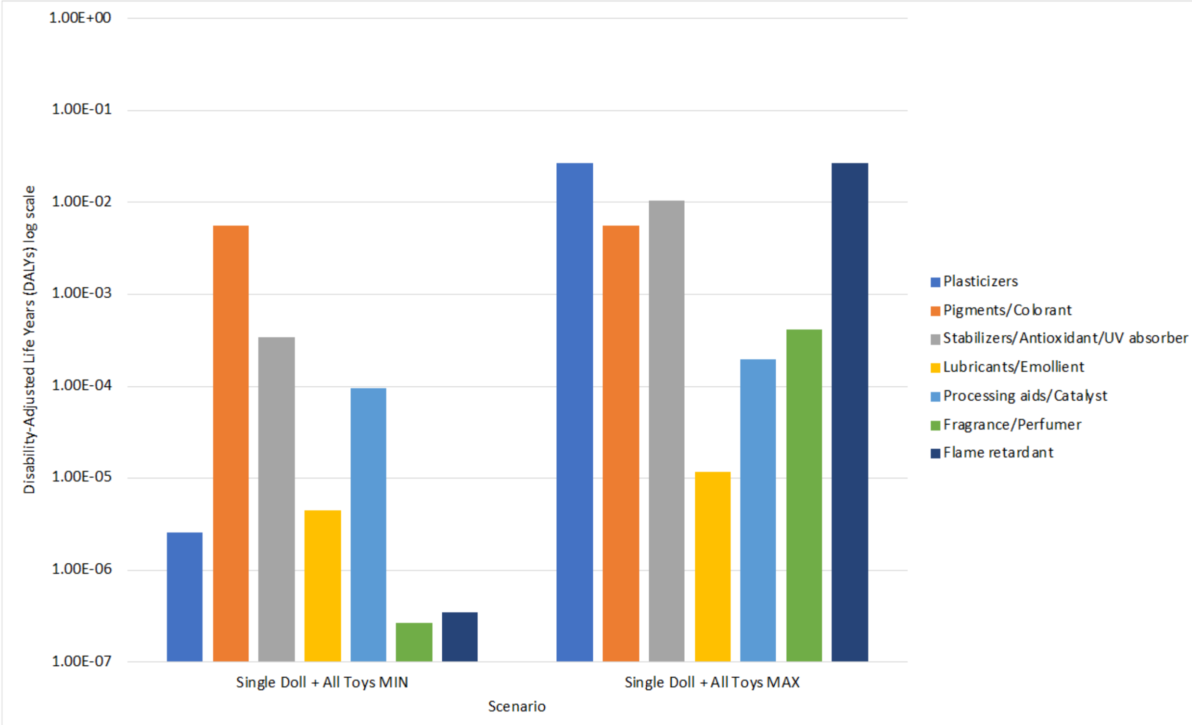


Table 9-3. Impacts of the Single Doll, All Toys and Combined Impacts, in Years, Days, Hours and Minutes of Healthy Life Lost

	ALL IMPACTS	Single doll MIN	Single doll MAX	All toys MIN	All toys MAX	Single doll + all toys MIN	Single doll + all toys MAX
	Plasticizers	2.45E-06	2.86E-03	1.24E-07	2.43E-02	2.58E-06	2.72E-02
	Pigments/colourants	5.67E-05	5.67E-05	5.59E-03	5.59E-03	5.65E-03	5.65E-03
	Stabilizers/antioxidants/UV absorbers	8.57E-06	1.91E-04	3.33E-04	1.04E-02	3.41E-04	1.06E-02
	Lubricants/emollients	9.88E-08	1.87E-07	4.37E-06	1.15E-05	4.46E-06	1.17E-05
	Processing aids/catalysts	7.93E-07	1.87E-05	9.41E-05	1.79E-04	9.49E-05	1.97E-04
	Fragrances/perfumers	3.42E-08	1.84E-06	2.30E-07	4.10E-04	2.64E-07	4.12E-04
	Flame retardants	9.34E-08	2.37E-02	2.59E-07	3.32E-03	3.52E-07	2.70E-02
YEARS	TOTAL	6.87E-05	2.68E-02	6.03E-03	4.42E-02	6.10E-03	7.11E-02
YEARS	TOTAL w/o pigment	1.20E-05	2.68E-02	4.32E-04	3.87E-02	4.44E-04	6.54E-02
YEARS	TOTAL w/o pigment + flame retardant	1.19E-05	3.07E-03	4.32E-04	3.53E-02	4.44E-04	3.84E-02
DAYS	TOTAL	0.03	9.80	2.20	16.15	2.22	25.95
DAYS	TOTAL w/o pigment	0.00	9.78	0.16	14.11	0.16	23.89
DAYS	TOTAL w/o pigment + flame retardant	0.00	1.12	0.16	12.89	0.16	14.01
HOURS	TOTAL	0.60	235.18	52.79	387.58	53.39	622.77
HOURS	TOTAL w/o pigment	0.11	234.69	3.78	338.58	3.89	573.26
HOURS	TOTAL w/o pigment + flame retardant	0.10	26.87	3.78	309.46	3.89	336.33
MINS	TOTAL	36.11	14111.07	3167.45	23254.90	3203.56	37365.97
MINS	TOTAL w/o pigment	6.33	14081.29	227.07	20314.52	233.40	34395.81

MINS	TOTAL w/o pigment + flame retardant	6.28	1612.19	226.94	18567.80	233.22	20179.99

9.B.4. Key takeaways

- Health impacts are associated with ingestion, dermal uptake and inhalation of chemicals in toys, from both playing with a single doll and from exposure to total toys in a room.
- Exposure to all toys in the room dominated the total health impacts of the child, and for the health effects associated with individual chemical functions in toys, except for the flame retardant in the MAX scenarios, for which using the single toy was the dominant source of health impacts.
- Plastic can contain a plethora of NIAS, including residues of processing aids, catalysts and other industrial chemicals, degradation products from chemical reactions, impurities and contaminants. These chemicals may be present in low weight fractions but can have high toxicity.

9.C. Case study: Plastic food packaging

9.C.1. Chemical composition

Based on data from Gerassimidou et al., 2022; Huang et al., 2024; Jang et al., 2024; and Wiesinger, 2024, we have weight fraction data for chemicals contained in plastic food packaging for 386 substances, almost all of which appear to be NIAS based on their presence at weight fractions below 0.1%.[121] The identified (386) chemicals equate to just 13% of the total number of chemicals shown to migrate from plastic food packaging, and the low weight fractions mean that the vast majority of the plastic chemical composition is unaccounted for in this available data, with critical data gaps for both particular polymers and products (Figure 9-5).[122] A third of the 386 chemicals are known or suspected endocrine disrupting chemicals and include bisphenols and phthalates with known health risks.[123]

Figure 9-5. Number of Chemicals With Available Weight Fraction Data by Polymer and Product

Count of Substance	Polymer_Summary																												
Product_group_Level3	(not specified)	Cellophane	EPS	HDPE	HIPS	LDPE	Multilayer plastic	Multilayer plastic, aluminium	Multilayer plastic, aluminium, paper	PA	PA, PET, PP	PC	PE	PET	PLA	PMMA	PP	PP/PE	PS	PVA	PVC	rubber	SAN	starch	VAE	(blank)
Packaging - Consumer packaging - Bags	34					2							11	1												
Packaging - Food packaging - Adhesives																11				8				12	29	
Packaging - Food packaging - Bags	8					53						5	15				33	1								
Packaging - Food packaging - Bottles	8			36		5						5	27	77	5		26		7		1					
Packaging - Food packaging - Films	34	5					32	12	2	4	16		54				58				59					
Packaging - Food packaging - Generic	25																5									
Packaging - Food packaging - Laminates																									14	
Packaging - Food packaging - Nets													22	32												
Packaging - Food packaging - PTTs	23		7	4	7	2						6	1	25			49		45		10	1	3			
Packaging - Food packaging - Raw material														2		1			11							
Packaging - Food packaging - Utensils	23																									
Packaging - Manufacturing packaging - Films				5		5																				
(blank)																										

Source: Spyridoula Gerassimidou et al., "Unpacking the Complexity of the PET Drink Bottles Value Chain." Yu-Qi Huang et al., "Disposable Plastic Waste and Associated Antioxidants." Mi Jang et al., "Hazardous Chemical Additives Within Marine Plastic." Helene Wiesinger, "Investigating Hazardous Chemicals in Plastics"

9.C.2. Scenario: Single boil-in-the-bag rice bag

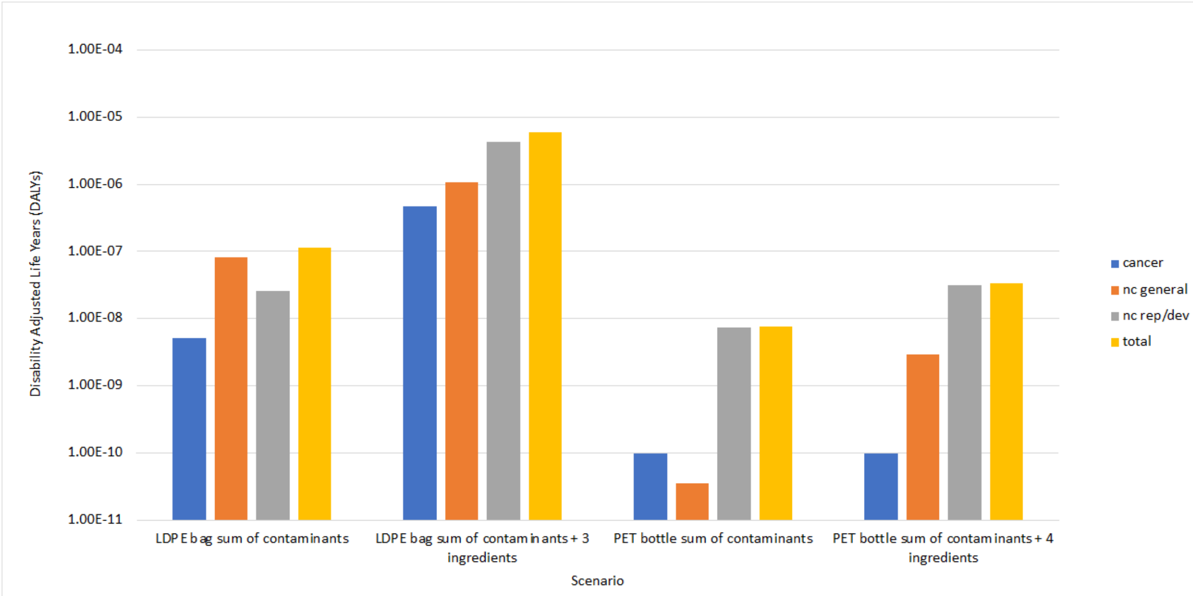
This scenario was based on consuming rice boiled in an LDPE bag for 20 minutes at 100°C (Figure 9-6). Based on data from Gerassimidou et al., 2022; Huang et al., 2024; Jang et al., 2024; and Wiesinger, 2024, weight fraction data was available for 29 chemicals in the LDPE bag, all of which appeared to be at levels of NIAS (<0.1% weight fraction).[124] We considered in addition three chemical additives, azacyclotridecan-2-one, acetyl tributyl citrate and 2,6-di-t-butyl-4-methylphenol, taken from a scientific study modelling chemical exposures from food contact materials.[125] Of the 32 chemicals included in our analyses, 28 were associated with reproductive/developmental and general non-cancer effects, while three were associated with cancer effects. The most harmful substance for reproductive/developmental and non-cancer was P-ethylphenol. The resulting loss of healthy life was between a tenth of a second and seven seconds depending on the inclusion of the chemical additives. While the additives themselves were no more harmful than the NIAS, they had a stronger influence on the overall health impacts of the LDPE bag because of their higher weight fraction.

9.C.3. Scenario: PET bottle

This scenario was based on a PET bottle containing water, stored at 20°C for eight hours (Figure 9-6).

- Weight fraction data was available from Gerassimidou et al., 2022; Huang et al., 2024; Jang et al., 2024; and Wiesinger, 2024, for 30 chemicals in PET bottles, mostly at levels indicating NIAS (<0.1%) and four at possible additive concentrations (but still constituting only 0.2% to 3%).[126]
- 28 of these chemicals were associated with reproductive/developmental effects, 27 with non-cancer and eight with cancer effects. The most toxic of those found were bisphenol A and formaldehyde for the reproductive/developmental effects, acetaldehyde and formaldehyde for cancer, alongside atrazine which may have been adsorbed by the PET bottle as this chemical is contained in pesticides banned for use in the EU, all at concentrations indicating NIAS (<0.1% weight fraction).
- DALYs associated with exposure to chemicals from PET bottles under these conditions appeared low at just a second of healthy life lost per bottle, but even including all chemicals identified based on having available weight fraction data in PET bottles would account for only 5% of the mass of the bottle.
- From the limited data we have on PET bottles, including the four chemical additives (>0.1% weight fraction in the PET bottles) relative to the identified NIAS alone, increased overall DALYs associated with chemical exposure from the bottle by an order of magnitude and by two orders of magnitude specifically for the non-cancer effects. If we had data for the full chemical composition of the PET bottle, the impacts may increase again.
- While the health impacts were relatively low, this may be more a function of limited data than real absence of harm.

Figure 9-6. DALYs Associated With Human Exposure to NIAS and Active Ingredient Chemicals in Food Packaging



Note: From left to right: (1) An LDPE bag for boil-in-the-bag rice with NIAS only (i.e., those identified at concentrations <0.1%); and (2) the same LDPE bag with NIAS and three additive ingredients; (3) a PET bottle with NIAS only; and (4) the same PET bottle with four active chemical ingredients

9.C.4. Key takeaways

- Plastic food packaging contains a high number of different NIAS that do not appear to correlate with polymer or product type, including some that have now been banned in certain locations in food contact materials (e.g., bisphenol A) and some that are likely contaminants from other sectors, also including EU-banned chemicals (e.g., atrazine used in agriculture).
- Much of plastic's chemical composition is unaccounted for in current data. We need transparency in terms of chemical composition in order to properly assess plastic and protect human health.
- Chemical simplification is the most effective way to remove risks, prioritizing removing additives of concern and preventing NIAS from forming or entering plastic.

Most of us are exposed to many different plastic products on a daily basis, from those used in buildings and transportation, textiles in furnishings and clothing, food packaging and food contact materials, household and personal care products, electronics, sports equipment and children's toys. The combined and potentially interacting effects of the total human "exposome" of plastic chemicals is likely to result in substantially greater effects than those that can be identified on a product-by-product basis.

9.C.5. Conclusion

- The same chemicals have been identified across multiple polymers and plastic products. While we may be exposed to low doses from each product, we could be exposed to much higher doses taking into account the aggregate exposure to chemicals in the multitude of products we are in contact with.
- Despite the same chemicals appearing across different products, the presence of individual chemicals, their weight fraction, the overall chemical diversity (number of different chemicals) and the resulting toxicity do not appear to be consistent for polymer or product types. This was also found in a study testing endocrine disruption of plastic food packaging from five different countries. [127] Without increasing data transparency, we cannot currently accurately predict the chemical composition of polymers and products and cannot rely on risk assessments conducted in specific conditions on specific products.
- We are exposed to many different chemicals with toxic effects for both cancer and non-cancer, the combination of which is important, both in terms of their additive effects and chemical interactions.

9.C.6. Key challenges and related recommendations

1. Data availability on chemical composition. We need mandatory transparency for chemicals across plastic life cycles.
2. Many chemicals are known to be harmful to human health, and many more could be but have not been tested. Chemical simplification is key to reducing the health impacts we know about and reducing the risks of introducing new risks by substituting chemicals.
3. Assessing chemical by chemical and product by product does not reflect the true exposure to plastic chemicals from across products. We need to move away from individual risk assessments to holistic analyses that seek to identify and remove hazards using a precautionary approach.

9.C.7. Methods annex

a) About the USEtox model

USEtox is an internationally recognized global reference model for assessing the human health impacts of chemicals. [128] USEtox was developed based on a series of model comparisons by an international team of experts between 2002 and 2008, under the auspices of the Life Cycle Initiative hosted by the United Nations Environment Programme. USEtox has been formally endorsed by the Life Cycle Initiative since 2013 and has been applied by a wide range of academic, public and private stakeholders – mostly in the context of using its characterization factors implemented in various life-cycle impact assessment methods. USEtox originally characterizes toxicity and ecotoxicity impacts from chemicals emitted primarily into the outdoor environment along product and service life cycles. Since its major releases in 2008 (version 1) and 2015 (version 2), USEtox has been continuously advanced and expanded, for example in terms of covered pathways, chemicals and application contexts. From its current beta release version 3, USEtox shows great potential to become a global reference model for assessing human toxicity and ecotoxicity impacts in a wider range of decision-making frameworks beyond LCA. [129] Through these developments, USEtox can improve the assessment and management of chemicals in the global environment, with the aim of creating safer, more sustainable systems that protect people and the planet.

The process for deriving characterization factors in USEtox can be summarized under three main categories: (1) a fate factor, quantifying how chemicals disperse in the environment; (2) an exposure factor, quantifying human contact with chemicals present in environmental media; and (3) an effect factor, quantifying effects per kilogram of human intake. The resulting characterization factor is that which is required to estimate the human health impact score in DALYs per kilogram of chemical emission or chemical in product. [130]

b) Health outcomes

Human health damages in USEtox account for carcinogenic impacts, general non-carcinogenic impacts, non-carcinogenic reproductive/developmental impacts and total impacts (carcinogenic and non-carcinogenic). [131] (See Table 9-4.) The scale of modelling in USEtox can be applied to represent disaggregated and/or cumulative health impacts resulting from: (1) the direct health impacts of exposure to chemicals through using a given product, (2) the indirect global health impacts resulting from exposure to chemicals emitted from that product to the environment, and (3) their subsequent transfer through different environmental compartments.

Table 9-4. Human health impacts assessed in USEtox.

Indicator	Description
Human carcinogenic toxicity	**Impact pathway:** Emission and increased concentration of chemicals in the environment
	Human health impacts: Morbidity and mortality due to increase in cancer incidence: mouth and oropharynx, oesophagus, stomach, colon and rectum, liver, pancreas, trachea, bronchus and lung, melanoma and other skin cancer, breast, cervix uteri, corpus uteri, ovary, prostate, bladder, lymphomas and multiple myeloma, and leukaemia
Human non-carcinogenic toxicity	**Impact pathway:** Emission and increased concentration of chemicals in the environment
	Human health impacts: Morbidity and mortality due to increase in non-cancer incidence: • Neuropsychiatric conditions: bipolar disorder, schizophrenia, epilepsy, dementia, Parkinson's disease, multiple sclerosis, obsessive-compulsive disorder, panic disorder • Sense-organ diseases: glaucoma, cataract • Cardiovascular diseases: rheumatic heart disease, ischaemic heart disease, inflammatory heart disease • Respiratory diseases: chronic obstructive pulmonary disease, asthma; diabetes mellitus • Digestive diseases: peptic ulcer, liver cirrhosis • Genitourinary diseases: nephritis and nephrosis, benign prostate hypertrophy

	• Musculoskeletal diseases: rheumatoid arthritis, osteoarthritis • congenital anomalies: abdominal wall defect, anencephaly, anorectal atresia, cleft lip, cleft palate, oesophageal atresia, renal agenesis, Down syndrome, congenital heart anomalies and spina bifida

Sources: Mark A. J. Huijbregts et al., *Human-Toxicological Effect and Damage Factors of Carcinogenic and Noncarcinogenic Chemicals for Life Cycle Impact Assessment*, 2005. Rosalie van Zelm, Mark A. J. Huijbregts, and Dik van de Meent, *USES-LCA 2.0—A Global Nested Multi-Media Fate, Exposure, and Effects Model*, 2009

c) Disability-adjusted life years

Cases of cancer and non-cancer in USEtox are translated to their equivalent impacts in DALYs. DALYs are an internationally standardized metric for human health that accounts for premature mortality and life lived with disability, disease, or states of less-than-optimal health due to different exposures and risk factors. As a metric, DALYs have been widely adopted by international health authorities such as the World Health Organization (WHO) and in global human health scientific research and monitoring as exemplified in the "Global Burden of Disease Study." [132]

The WHO defines a DALY as follows: "One DALY represents the loss of the equivalent of one year of full health. DALYs for a disease or health condition are the sum of the years of life lost to due to premature mortality and the years lived with a disability due to prevalent cases of the disease or health condition in a population." [133]

DALYs offer a coherent and interpretable human health metric for assessing the health impacts of chemicals, and the USEtox model provides a holistic, state-of-the-art framework to estimate multiple routes of human exposure. DALYs facilitate assessment, aggregation and comparison of human health effects arising from multiple environmental stressors (i.e., different chemicals and different human exposure routes) and different health outcomes (i.e., different diseases and their impact on the loss of health life through living with disease or disability and due to premature death).

The DALYs derived from USEtox assessments have a number of inherent uncertainties that relate to (1) the quality and availability of chemical input inventory data, e.g., the chemical composition of plastic products; (2) the model input data and assumptions, e.g., the quantities of chemicals transferred from the product to the human via direct contact or between different environmental compartments); (3) the dose-response relationships for estimating disease, which are primarily extrapolated from animal testing studies; and (4) the assumptions and disability weightings of DALYs associated with a given disease. [134]

DALYs in themselves also have several limitations. The methods of calculating DALYs have evolved significantly since 1993 and have been subject to critique and criticism. [135] The primary points of contention have stemmed from the relevance of life expectancy reference points in the reality of international disparities and global change, the calculation of incidence versus prevalence of disease, initial age-discounting in the methods which meant that life lost early or late in the human life course was devalued, and the disability weights applied for different diseases which have received criticism for being developed without sufficient transparency and for conveying a devaluing of life lived with certain health conditions.[136]

Nevertheless, DALYs offer a useful, internationally relevant metric for considering the aggregate health impacts of plastic chemicals and their associated disease outcomes, and for situating these health impacts in the context of the global burden of disease.

10. Low-end results for System Transformation

This section presents the results of the low-end System Transformation scenario, as described in section 6.A.

Table 10-1. Annual Plastic Mass at Key Life-Cycle Stages Under BAU in 2025 and 2040 and Change in Mass Under System Transformation Low and High, in Mt

	BAU		System Transformation Low		System Transformation High	
Life-cycle stage	**2025**	**2040**	**2040**	**% change from BAU 2040**	**2040**	**% change from BAU 2040**
Open-loop mechanical recycling	48	54	94	75%	71	33%
Closed-loop mechanical recycling	19	21	60	190%	61	190%
Chemical conversion (P2P)	<0	<0	<0	920%	<0	1800%
Chemical conversion (P2F)	<0	<0	<0	440%	<0	480%
Incineration	46	62	85	36%	75	20%
Controlled landfill	210	270	230	-16%	200	-27%
Uncontrolled landfill	44	64	57	-12%	51	-21%
Open burning	56	150	46	-68%	21	-85%
Aquatic pollution	22	42	18	-57%	11	-73%
Terrestrial pollution	49	98	30	-70%	14	-85%

Table 10-2. Annual Mass of Microplastic Pollution to the Aquatic and Terrestrial Environments Under BAU in 2025 and 2040 and Change in Mass Under BAU, System Transformation Low and System Transformation High, in Mt

	BAU		System Transformation Low		System Transformation High	
Microplastic source	**2025**	**2040**	**2040**	**% change from BAU 2040**	**2040**	**% change from BAU 2040**
Agriculture	1.900	3.200	2.400	-24%	1.700	-48%
Paint	6.400	9.600	8.900	-7%	8.400	-13%
Personal care products	0.053	0.066	0.013	-81%	0.006	-91%
Pellets	0.110	0.170	0.046	-73%	0.006	-96%
Recycling	2.000	2.200	1.200	-44%	0.270	-88%
Textiles	0.052	0.074	0.013	-83%	0.011	-85%
Tyres	6.500	10.000	5.900	-42%	4.600	-55%

Total	**17.000**	**26.000**	**19.000**	**-27%**	**15.000**	**-41%**

Table 10-3. Annual Packaging Material Mass in the Plastic Packaging Sector Under BAU, System Transformation Low and System Transformation High in 2040, in Mt

Material	BAU	System Transformation Low	System Transformation High
Single-use plastic	210	120.0	62.0
Single-use metal	0	5.5	5.8
Single-use paper	0	12.0	15.0
Single-use glass	0	40.0	39.0
Single-use compostables	0	2.3	3.3
Reusable plastic	0	3.2	5.7
Reusable metal	0	1.8	2.7
Reusable glass	0	12.0	24.0
Total single-use materials	**210**	**180.0**	**120.0**
Total reuse materials	**0**	**17.0**	**32.0**

Table 10-4. Annual GHG Emissions, DALYs, Costs and Jobs under BAU, System Transformation Low and System Transformation High in 2040

Impact	BAU	System Transformation Low	System Transformation High
GHG emissions (gigatons of CO_2e)*	4.2	3.4	2.8
DALYs (millions)†	9.8	6.1	4.5
Costs (trillions)‡	US$2.4	US$2.1	US$1.8
Jobs (millions)§	61.0	63.0	59.0

*Total emissions reflect those associated with all life-cycle stages modelled, as described in section 5.B. These results include emissions associated with the reuse and substitute materials as modelled in the packaging sector under System Transformation.

† Total DALYs reflect those associated with the plastic life-cycle stages modelled (and do not include those associated with reuse and substitute materials), as described in section 5.A.

‡ Total costs include capital and operating expenditures for the life-cycle stages modelled, as described in section 5.C. These results include costs associated with the reuse and substitute materials as modelled in the packaging sector under System Transformation.

§ Total jobs include those associated with the life-cycle stages modelled, as described in section 5.C. These results include costs associated with the reuse and substitute materials as modelled in the packaging sector under System Transformation.

11. Endnotes

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includes GHG emission factors for virgin polymer production, we do not use this data in Pathways and instead use estimates from Karali, Khanna, and Shah, 2024.

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