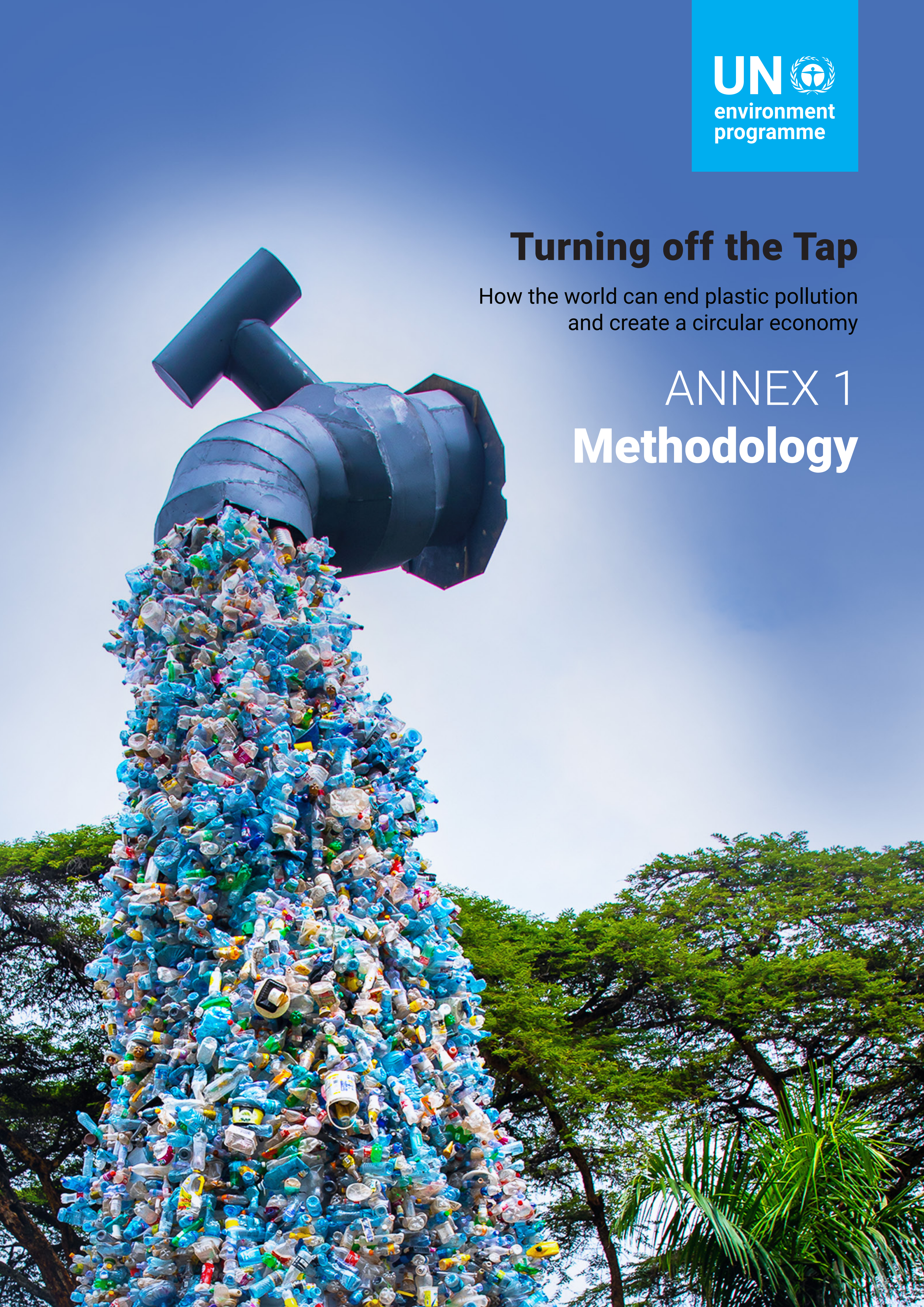

UN environment programme

Turning off the Tap

How the world can end plastic pollution and create a circular economy

ANNEX 1
Methodology

This is Annex 1: Methodology of "**Turning off the Tap: How the world can end plastic pollution and create a circular economy**" (ISBN No: 978-92-807-4024-0). UNEP does not accept responsibility for the accuracy or completeness of the contents of this Methodology and shall not be liable for any loss or damage that may be occasioned directly or indirectly through the use of, or reliance on, the contents of this Methodology.

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Contents

Photo: UNEP

Annex 1.1 **Key metrics and assumptions in the business-as-usual and systems change scenarios**

Most of the modelling of plastic flows and related capital and operational expenditure, job implications and greenhouse gas (GHG) emissions presented in this report is based on the 'Breaking the Plastic Wave' report (The Pew Charitable Trusts and Systemiq 2020). A thorough description of the assumptions and model used is documented in Lau *et al.* (2020)[1]. In short, the core of the modelling is a system map that highlights the main flows and stocks of the global plastic system for both macroplastics and microplastics (see Figure A1.1). Data for the size of each box and arrow in the system map were collected for each geographic archetype, for each plastic category and for each of the scenarios. Where data was unavailable expert opinion was collected, and for each data set uncertainty was characterised with a pedigree scoring framework. Due to the lack of sufficiently comprehensive and detailed data sets for validating the model, sensitivity analyses were conducted to assess the influence of key variables and assumptions on the results, as well as to identify the key drivers in the system (The Pew Charitable Trusts and Systemiq 2020).

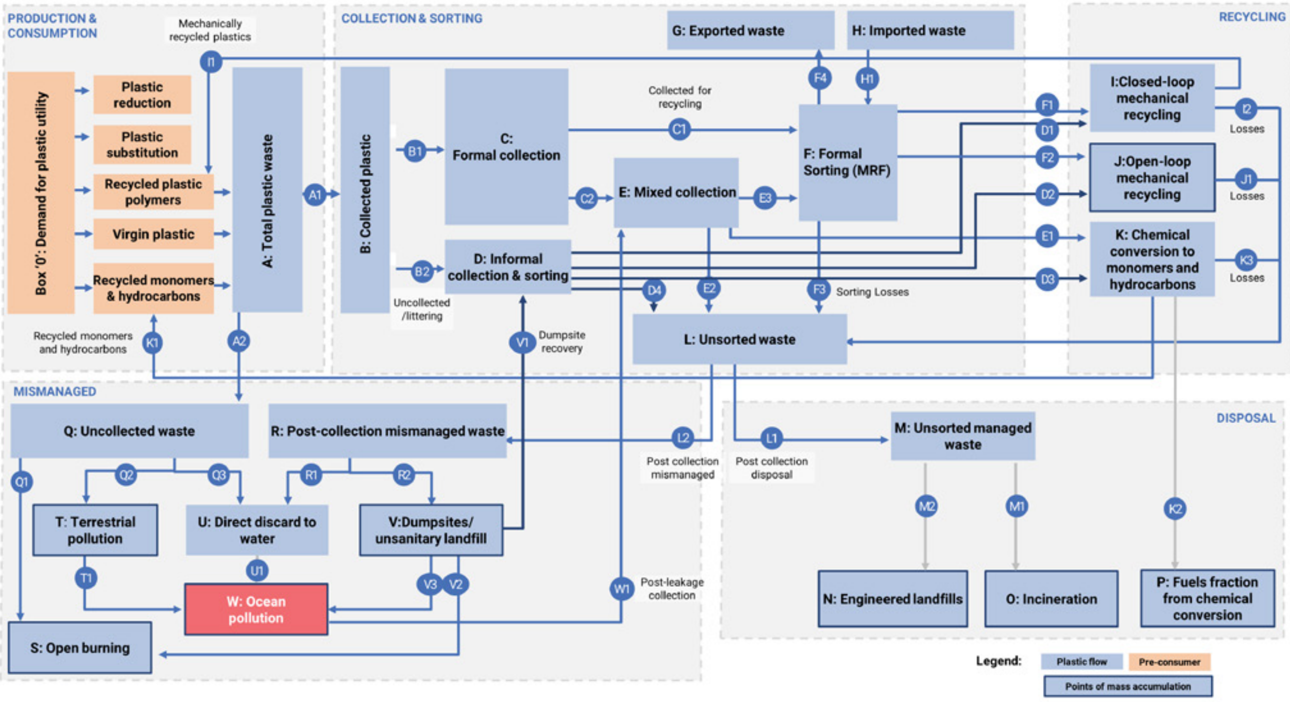

Figure A1.1: **'Breaking the Plastic Wave' global plastic system map.**

Source: The Pew Charitable Trusts and Systemiq 2020

Following the quantification of volumes for each of the boxes and arrows, these were coupled with economic data (e.g. costs per ton), climate data (e.g. GHG emissions per ton) and social data (e.g. employment per ton) to quantify the total economic, environmental and social implications for the system in each scenario.

[1] Full materials appear in Science: https://www.science.org/doi/10.1126/science.aba9475#supplementary-materials. Additional information is available upon request. The complete codebase, all input files and raw outputs for model runs are available at https://dx.doi.org/10.5281/zenodo.3929470.

Box A1.1: **What is the business-as-usual scenario?**

Under the business-as-usual (BAU) scenario (for plastics in short-lived products only), population and per capita consumption continue to grow according to current forecasts, and the global plastic system - the current policy framework, market dynamics and consumer behaviours - remains as it is today. In this scenario, population growth and consumption per capita is estimated to lead to a growth of short-lived plastic pollution from 90 million metric tons in 2016 to 240 million metric tons in 2040.

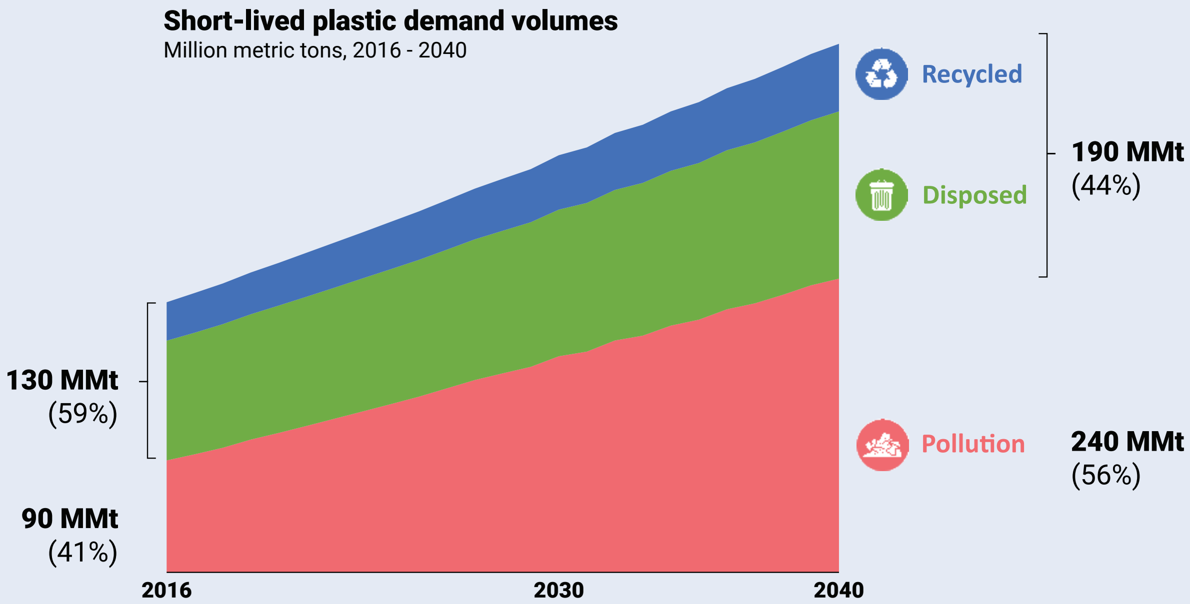

Figure A1.2: **Fate of the short-lived plastic volumes in a business-as-usual scenario.**

Source: The Pew Charitable Trusts and Systemiq 2020.

In the business-as-usual (BAU) scenario (see Box A1.1), analysis forecasts the production of plastics from short-lived products will double in volume by 2040, plastic pollution in the environment will grow by more than two and half times and the stock of plastics in the ocean will more than quadruple, as shown in Figure A1.3.

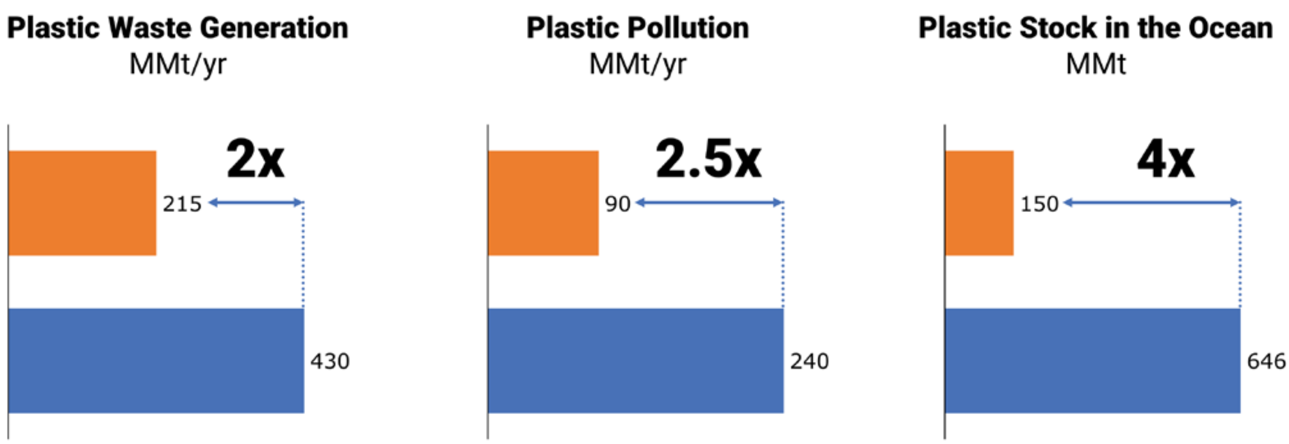

Figure A1.3: **Business-as-usual projections for plastic waste indicators.**

Source: The Pew Charitable Trusts and Systemiq 2020.

1.1.1 **Current commitments**[2]

Governments and the private sector have already made some commitments to cut plastic waste, including regulations (e.g. bans or levies on certain single-use plastic products) and pledges (e.g. company targets to reduce plastics or to increase recyclability in their designs). Analysis shows current commitments will only reduce annual volumes of plastic pollution in 2040 by 7-8 per cent[3] compared to the BAU scenario, or the equivalent of preventing around 19 million tons of plastic pollution annually by 2040. Therefore, these existing government policies and corporate initiatives remain insufficient to meet the challenge of eliminating or even significantly reducing plastic pollution.

1.1.2 **Impact of the systems change scenario**

The system-wide actions in this scenario can dramatically reduce annual plastic pollution by 2040. In 2016 there were approximately 90 million metric tons (MMt) per year of pollution; in a BAU Scenario this could reach 240 MMt per year by 2040. However, the actions in the system change scenario can bring this down to 44 MMt per year by 2040 (a reduction of 80 per cent compared to BAU and a reduction of 50 per cent compared to 2016). In addition to significantly reducing plastic pollution, the systems change scenario also brings lower GHG emissions, lower costs to governments and higher job creation, as shown in Figure A1.4.

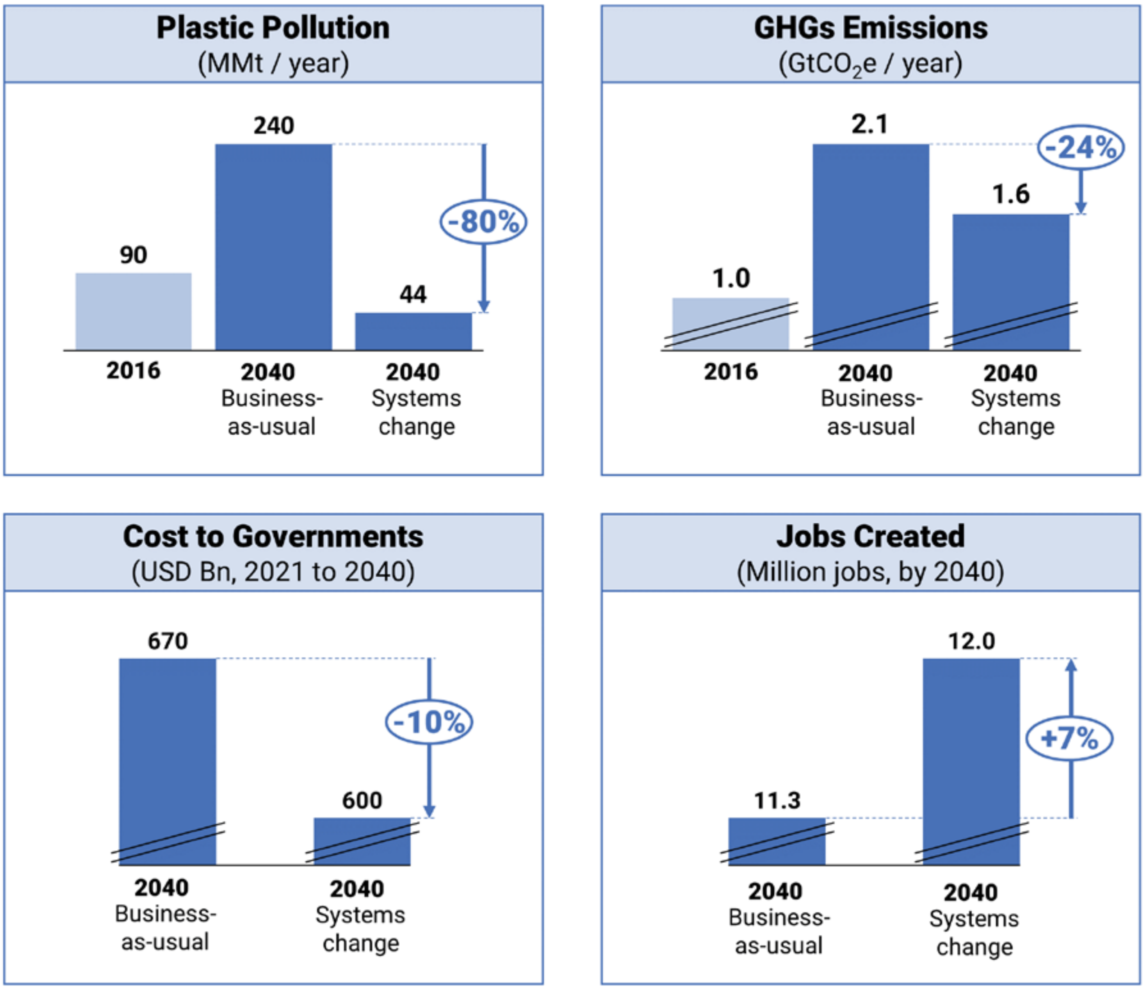

Figure A1.4: **Comparison of plastic pollution, GHG emissions, cost and job creation between scenarios.**

Source: The Pew Charitable Trusts and Systemiq 2020.

[2] This level of commitment takes into consideration the commitments up to mid-2022.
[3] This includes new single use plastic products bans, new collection for recycling programs in middle-income cities and new impact on plastic waste imports from national bans or Basel Convention amendments.

The integrated systems change scenario results in a 24 per cent reduction in annual plastic-related GHG emissions compared to the BAU scenario. Different solutions have different GHG profiles (see Figure A1.5), but the reduction in both production and conversion of virgin plastic, and the decrease in open burning, are the main drivers of overall emissions reduction.

Globally, government costs related to the plastic system are estimated to decrease by 10 per cent compared to a BAU scenario, driven by a decrease in plastic waste volumes to manage, as demand is reduced and product designs enhance circularity. This will reduce budgetary burdens on municipalities for waste collection and sorting. However, this reduction in government cost will mostly happen in high-income countries, while low- and middle-income countries will see their waste management costs increase, driven by increases in population, consumption per capita and infrastructure costs for reuse and recycling in most of those countries (see sections 1.1.4 and 1.1.5 for details).

By 2040, the systems change scenario creates 700,000 more jobs globally in the plastic system than the BAU scenario. While employment decreases in the virgin plastics production industry and plastic conversion, new jobs will arise in paper and compostables manufacturing, new business models and the recycling industry (see section 1.1.6).

Table A1.1: **Overall impact comparison of the systems change (SC) vs. business-as-usual (BAU) scenarios in 2040 and baseline in 2016.**

Global Volumes of plastic from short-lived products	2016	2040 BAU	2040 SC
A. Utility demand currently met by short-lived plastic (MMt per year)	**220**	**430** (x2 vs. 2016)	**430** (x2 vs. 2016)
B. Plastic volumes prevented via reduce, reuse and new delivery models (MMt per year)	n.a.	n.a.	**-130** (-30% of A)
C. Plastic volumes prevented via reorient and diversify (MMt per year)	n.a.	n.a.	**-70** (-17% of A)
D. Plastic volumes consumption (A-B-C) (MMt per year)	**220**	**430**	**230** (x1 vs. 2016) (-47% vs. BAU)
E. Plastic recycling out of total (MMt per year)	**31**	**55** (x1.8 vs. 2016)	**84** (x2.7 vs. 2016) (+50% vs. BAU)
F. Plastic safely disposed out of total (MMt per year)	**97**	**136** (x1.4 vs. 2016)	**101** (x1 vs. 2016) (-26% vs. BAU)
G. Plastic pollution (A-B-C-E-F) (MMt per year)	**91**	**240** (x2.5 vs. 2016)	**44** (x0.5 vs. 2016) (-80% vs. BAU)
GHG emissions (Gigatons CO2e/ year)	**1.0**	**2.1**	**1.6** (-24% vs. BAU)
Cost to governments (Present Value 2021-2040 USD Billion)	n.a.	**670**	**600** (-10% vs. BAU)
Incremental employment (Million jobs)	n.a.	**11.3**	**12.0** (+0.7 vs. BAU)

1.1.3 **GHG emissions - comparison per type of plastic life cycle**

Different solutions and plastic life cycles have very different GHG profiles, with elimination of plastics in the design, reuse schemes and mechanical recycling as the options that emit the least (Figure A1.5).

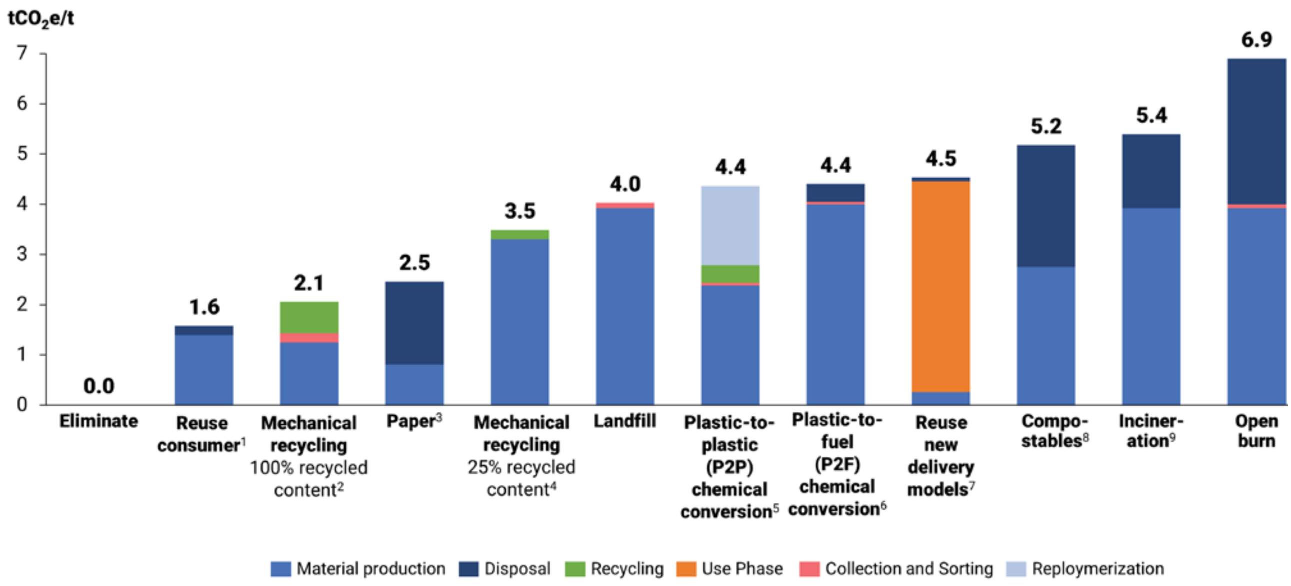

Figure A1.5: **GHG Emissions - Comparison per type of plastic life cycle.**

Source: The Pew Charitable Trusts and Systemiq 2020.

Notes on data used:

1. Production and disposal emissions were based on how much less waste would be produced (65 per cent less). 'Disposal' in this lever includes all end-of-life emissions, including collection, sorting and recycling.
2. Valid for both closed-loop and open-loop recycling. This assumes 100 per cent recycled content, which entails the collection and sorting of a larger proportion of waste to account for losses.
3. The average life-cycle emissions of paper or coated paper packaging per metric ton, multiplied by an average material weight increase from plastic to paper of 1.5. Emissions differ depending on how the paper is sourced. Disposing includes all end-of-life emissions including recycling.
4. Valid for both closed-loop and open-loop recycling. This assumes 25 per cent recycled content, which entails the collection and sorting of a larger proportion of waste to account for losses. The remaining 75 per cent is fulfilled by virgin plastic production.
5. Emissions include the repolymerization of naphtha as well as the pyrolysis process itself. It should be noted that data for GHG emissions for this technology are limited. See also topic sheet '**Chemical recycling**'.
6. Does not include the emissions from burning the fuel, as we assume that it replaces regular fuel with a similar GHG footprint. It should be noted that data for GHG emissions for this technology are limited. See also topic sheet '**Chemical recycling**'.
7. Production and disposal emissions were based on how much less waste would be produced (88 per cent less). 'Disposal' in this lever includes all end-of-life missions, including collection, sorting, and recycling; use-phase emissions were assumed to be the same as traditional plastics, although in practice they could be much lower once new delivery models reach scale.
8. Life-cycle emissions from polylactic acid (PLA) per metric ton.
9. The emissions for incineration are adjusted to reflect the emissions replaced from generating an equivalent amount of energy with average emissions.

1.1.4 **Government cost by region - comparison of systems change scenario vs. business-as-usual**

The total global cost to governments for managing plastic waste in the systems change scenario (present value of cost between 2021 and 2040) is estimated at USD 600 billion. This represents a 10 per cent reduction globally versus USD 670 billion cost to manage a business-as-usual system.

Low- and middle-income countries however will see costs to governments increase by around 15 per cent, from USD 241 billion to USD 278 billion as they need to heavily expand collection and prepare for population and consumption growth.

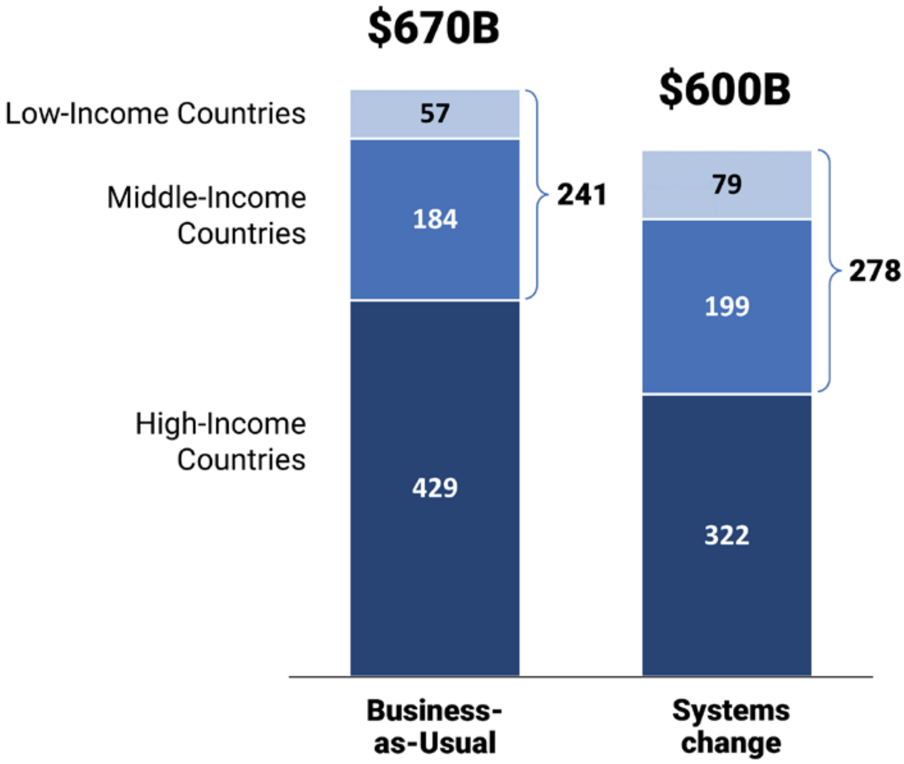

Figure A1.6: **Government cost by region - comparison of SC vs. BAU scenarios. USD billions, present value of 2021-2040.**

Source: The Pew Charitable Trusts and Systemiq 2020.

Photo: Getty Images

1.1.5 **Global system cost - comparison of systems change scenario vs. business-as-usual**

Reduce actions and the Reuse shift are the most attractive from an economic perspective, often representing a net saving solution. Plastic elimination, such as through bans and product redesign, is assumed to have zero cost; therefore, each metric ton of eliminated plastic would save the full cost of one metric ton of plastic in the BAU plastics value chain. Mechanical recycling offers a saving in low- and middle-income countries, but a cost in high-income countries due to higher labour costs. Reorient and diversify is the most expensive option, as more than a metric ton of paper is required to substitute a metric ton of plastic.

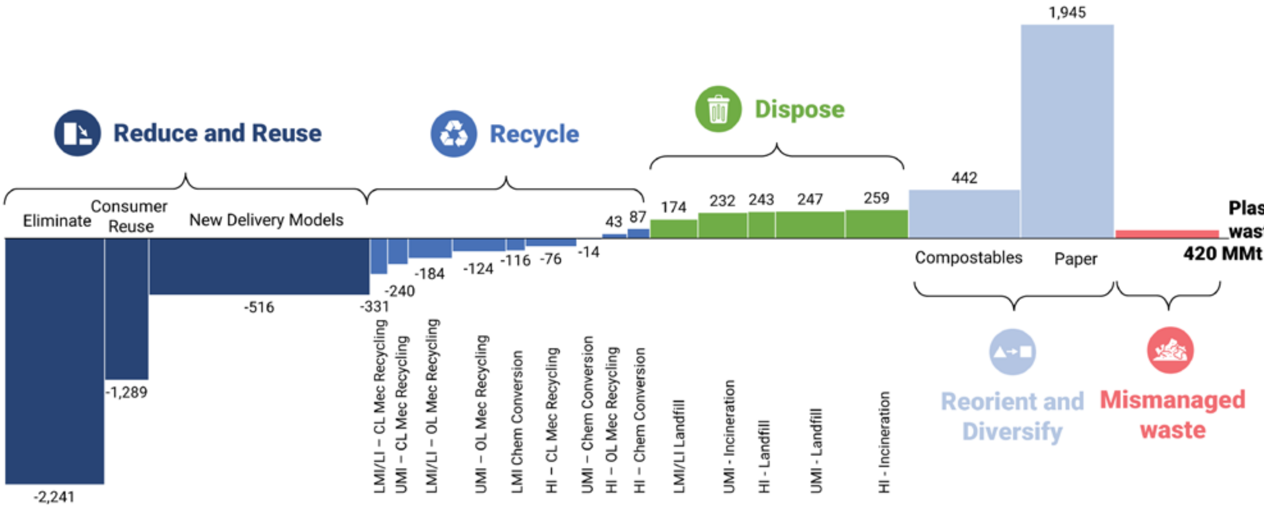

Figure A1.7: **Total system cost in USD/metric ton of plastic (systems change scenario vs. business-as-usual).**

Source: The Pew Charitable Trusts and Systemiq 2020.

Notes on data used:
HI= High-Income Country, UMI= Upper Middle-Income country, LMI=Lower Middle-Income Country, LI=Low-Income Country. The X axis of this chart shows the mass (million metric tons) of plastic waste per treatment type under the systems change scenario in 2040. The Y axis represents the net economic cost (USD) of that treatment, including opex and capex, for the entire value chain needed for that treatment type (for example, mechanical recycling costs include the cost of collection and sorting). Negative costs (on the left) represent a savings to the system relative to BAU, while positive costs reflect a net cost to the system for this treatment type. Costs near 0 mean that their implementation is near 'cost neutral' to the system. Subsidies, taxes or other 'artificial' costs have been excluded; this graphic reflects the techno-economic cost of each activity. The costs shown do not necessarily reflect today's costs, but costs that could be achieved after the system actions are implemented, including design for recycling and other efficiency measures. Where costs in different archetypes were similar, we combined the figure stacks for simplification and took a weighted average of the cost per archetype. The cost of mismanaged waste, such as plastic in the environment, has not been factored in because the price of externalities caused by plastic pollution is not quantified in this graph (see Annex 1.2).

Table A1.2: **Costs, jobs and GHG emissions per ton of processes and technologies used along the life cycle of plastics.**

Source: Developed from The Pew Charitable Trusts and Systemiq 2020.

Process / Technology	**CAPEX** (USD/input ton capacity)		**OPEX** (USD/input ton/year)		**Jobs operation** (jobs/1000 ton)		**GHG emissions** (CO2e/ton)		**Co-products per ton of input**	
	Global North	Global South	Global North	Global South	Global North	Global South	Global North	Global South	Global North	Global South
Reuse (collection; reverse logistics; washing…)	$196-$322	$138-$322	$1,027-$1,290	$726-$1,286	5.6-13.3	14.1-16.2	1.6-4.5		~5-10 tons of utility	
Plastic production	$338		$1,013		8		2.67		1 ton of output	
Plastic conversion	$223		$668		5		1.31		1 ton of output	
Collection waste – URBAN	$64	$35	$149	$81	2.3	6	0.02		1 ton of output	
Collection waste – RURAL	$86	$47	$202	$109	2.3	6	0.02		1 ton of output	

Sorting	$52	$39	$156	$117	1.7	0.05		0.8 ton of output	
Mechanical recycling	$120-$160	$90-$140	$410-$569	$307-$452	3	0.48	0.77	0.73 ton of output	
Chemical recycling[4]	$153	$116	$402	$289	1.3	2.97	3.17	0.54 (0.48-0.64) ton of output	
Use as co-fuel in cement kilns[5]	N/A	$15	N/A	$14	1.3	N/A	N/A	0.4 ton of RDF	
Engineered landfill	$23	$23	$8	$8	0.1	0.01		N/A	
Incineration with energy recovery[6]	$27	$21	$63	$28	0.1	1.4		$44 of energy ~525kWh / ton	$34 of energy ~400kWh / ton

1.1.6 **Jobs creation - comparison per step across plastic life cycle**

Under the systems change scenario, 700,000 net new formal jobs will be created by 2040 to fulfil demand for plastic services, including reuse schemes and new delivery models and the production of compostables, compensating losses of jobs in steps of the value chain connected to virgin plastic production (Figure A1.8). Table A1.3 provides further detail of total job changes across each step of the plastics life cycle.

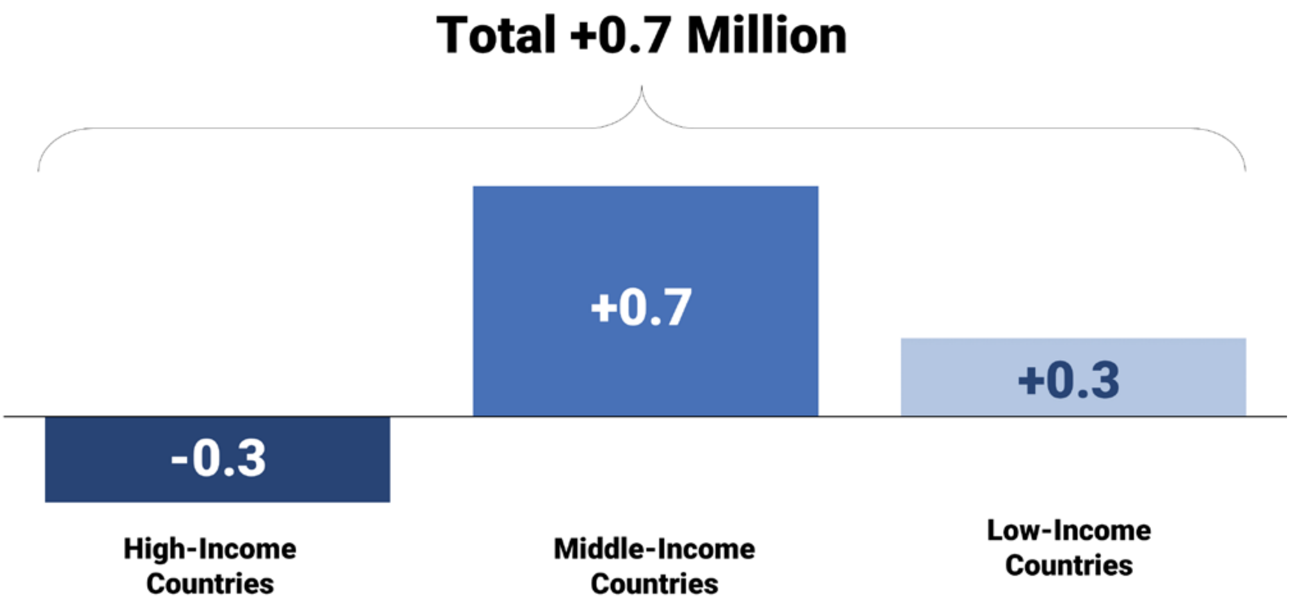

Figure A1.8: **Job creation in different income groups, systems change scenario minus business-as-usual.**

Source: The Pew Charitable Trusts and Systemiq 2020.

[4] Diverse technologies grouped under the denomination 'chemical recycling'; for a more refined overview see García-Gutiérrez *et al.* (2023)
[5] The cost is per ton of input, but for every ton of input you only get approximately 40% of refuse-derived fuel (RDF). A ton of input typically contains a high share of organics, driving the cost per ton of plastic even higher. RDF competes with very cheap coal, so the revenue from selling RDF is not enough to cover its opex. The economics only work in areas near kilns (otherwise transportation costs can drive costs significantly up), which are not ubiquitous. Also, plastic has a lower calorific value vs coal (~2,800 kcal/kg vs ~5,800 kcal/kg) so there is a limit to how much plastic can be used in cement kilns before falling below minimum heat requirements. According to research by Nexus3, the use of RDF to replace coal reduced CO_2 emissions by 27% and 12%, with 30% and 15% substitution rates for all cement types.
[6] The running costs are net of the revenues that appear in the last column.

Table A1.3: **Total jobs in different parts of the short-lived plastics value chain in the current market, and under business-as-usual and systems change scenarios.**

Source: The Pew Charitable Trusts and Systemiq 2020.

	Current	Business-as-usual	Systems change	Comparison
	2020	2040	2040	2040 SC minus BAU
Virgin plastic production	SC minus BAU	3,200,000	1,450,000	-1,750,000
Plastic conversion	1,230,000	2,100,000	1,120,000	-980,000
Formal collection	670,000	1,080,000	790,000	-290,000
Informal collection	3,270,000	4,680,000	3,930,000	-750,000
Sorting	60,000	90,000	110,000	20,000
Mechanical recycling	100,000	165,000	220,000	55,000
Chemical conversion	1,000	2,000	30,000	28,000
Thermal treatment	4,000	8,000	4,000	-4,000
Engineered landfills	6,500	5,000	5,000	0
Reduce - Reuse	-	-	180,000	180,000
Reduce - New Delivery Models	-	-	1,180,000	1,180,000
Substitute - Paper	-	-	690,000	690,000
Substitute - Coated paper	-	-	550,000	550,000
Substitute - Compostables	-	-	1,770,000	1,770,000
= Total jobs	**7,210,000**	**11,330,000**	**12,030,000**	**700,000**

1.1.7 **Additional changes for the systems change scenario**

Two additional scenarios were modelled that did not exist in the report 'Breaking the Plastic Wave'. The first is an analysis of the impacts of not building any new incineration capacity globally after 2020, and shifting all the waste that would have gone to new incineration capacity to engineered landfills. For the purpose of this scenario we assume that the cost per ton (opex and capex), the GHG per ton, and the jobs per ton for both engineered landfills and for incinerators stay as they are today. The total waste diverted from incineration to landfill is 172 MMt of plastic globally over a 20-year period (2021 to 2040).

The second new scenario models a tripling of mechanical recycling capacity by 2040 (relative to 2016) reaching 129 MMt globally, instead of 'only' doubling, as is assumed in the systems change scenario. This assumes that the extra amount of plastic waste, that would otherwise go to landfill, can be designed to be mechanically recyclable and that the economics of sorting and mechanical recycling are attractive enough to justify these investments into additional sorting and recycling capacity; an ambitious legally binding instrument agreed by the end of 2024 could set the enabling conditions and economic incentives to make this possible.

Annex 1.2 **Methodology for the economic analysis**

The methods applied in the economic analysis used in section 1.4 of the report are described in the following pages.

The following steps were implemented for the estimation of the economic impact of plastic pollution at the systems level. First, literature was reviewed on the causality existing between plastic pollution and resulting social, economic and environmental impact. Second, literature was reviewed to collect information on both available methods and cost coefficients to perform an economic valuation of the social, economic and environmental impact of plastic pollution. Third, the modelling of plastic flows (described in Annex 1.1 above) was reviewed to identify what flows and stocks could be used to perform the economic valuation of the various impacts of plastic pollution (i.e. what cost coefficients could be associated with specific plastic stocks and flows in the model). Fourth, an Excel-based model was developed, to perform a simple Cost Benefit Analysis (CBA) that includes direct costs (i.e. investment and operation and maintenance), as well as additional indirect social, economic and environmental costs. This model includes data inputs (i.e. plastics stocks and flows, and cost coefficients) and formulas for the estimation of the monetary direct, indirect or induced cost of plastic pollution. Fifth, different scenarios were analyzed with the model, including different policy ambition (e.g. in the BAU and Systems Change Scenarios), different coefficients for the economic valuation and different assumptions on discounting.

Merkl and Charles (2022) provide an overview of the thousands of literature references providing quantitative links between specific chemicals used in plastics and harms caused to human health, as well as the estimate of different social costs linked to plastics and the likeliness of consensus on causation (see Figure A1.9).

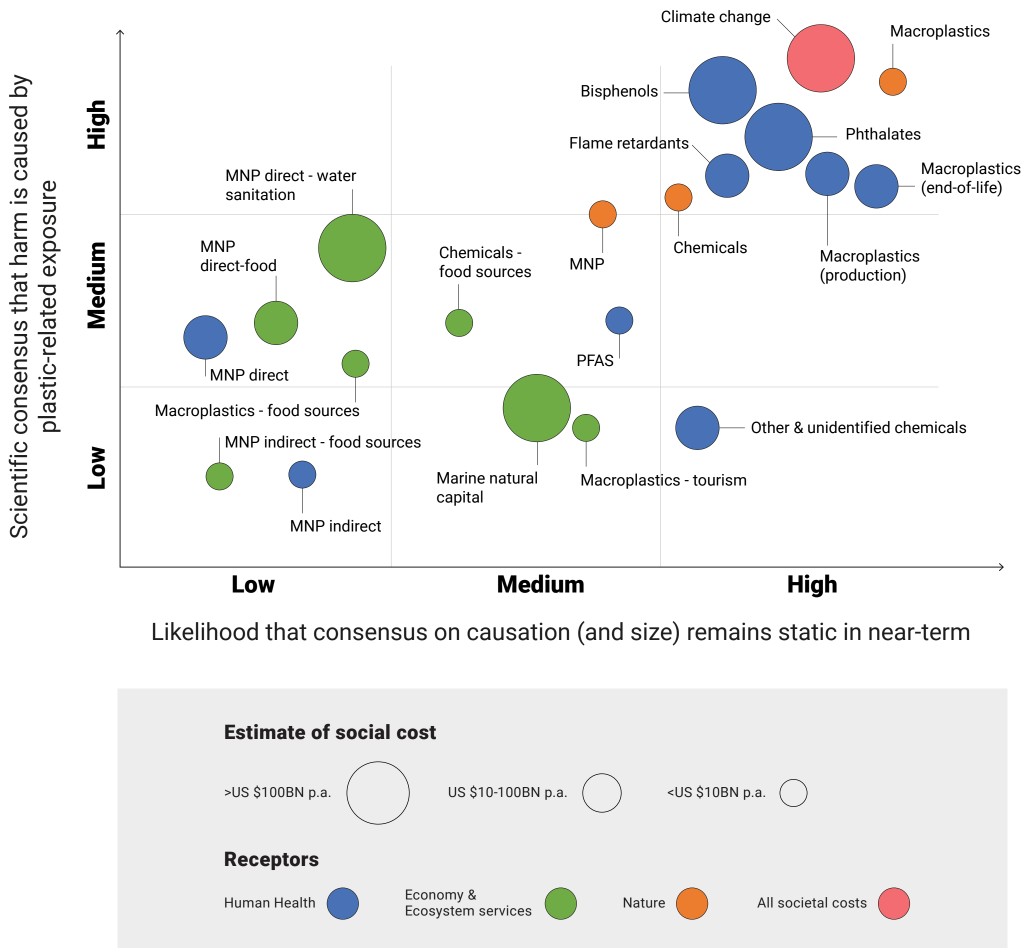

Figure A1.9: **Estimate of social costs related to plastics and future consensus on causation.**

Source: Merkl and Charles 2022. See https://cdn.minderoo.org/content/uploads/2022/10/13131230/The-Price-of-Plastic-Pollution-Annex-1.pdf for more details and calculations.

1.2.1 **Linking modelled flows to environmental and social costs**

In this study, the calculation of externalities related to the production, recycling and end-of-life management of plastics is based on the respective flows generated by the plastics model and coefficients sourced from the literature. For instance, the externality 'marine ecosystem service cost of plastic waste' is calculated based on the sum of plastic flows that are discharged into the ocean and an average cost per ton of plastic disposed in the ocean. The same approach is used for the other flows of the model for which a coefficient could be identified. Figure A1.10 illustrates the flow chart of the plastics model and the flows to which coefficients were applied. The coefficients (numbered) applied are presented in Table A1.4.

Global plastic system map Based on GHG emissions Based on tons of plastic

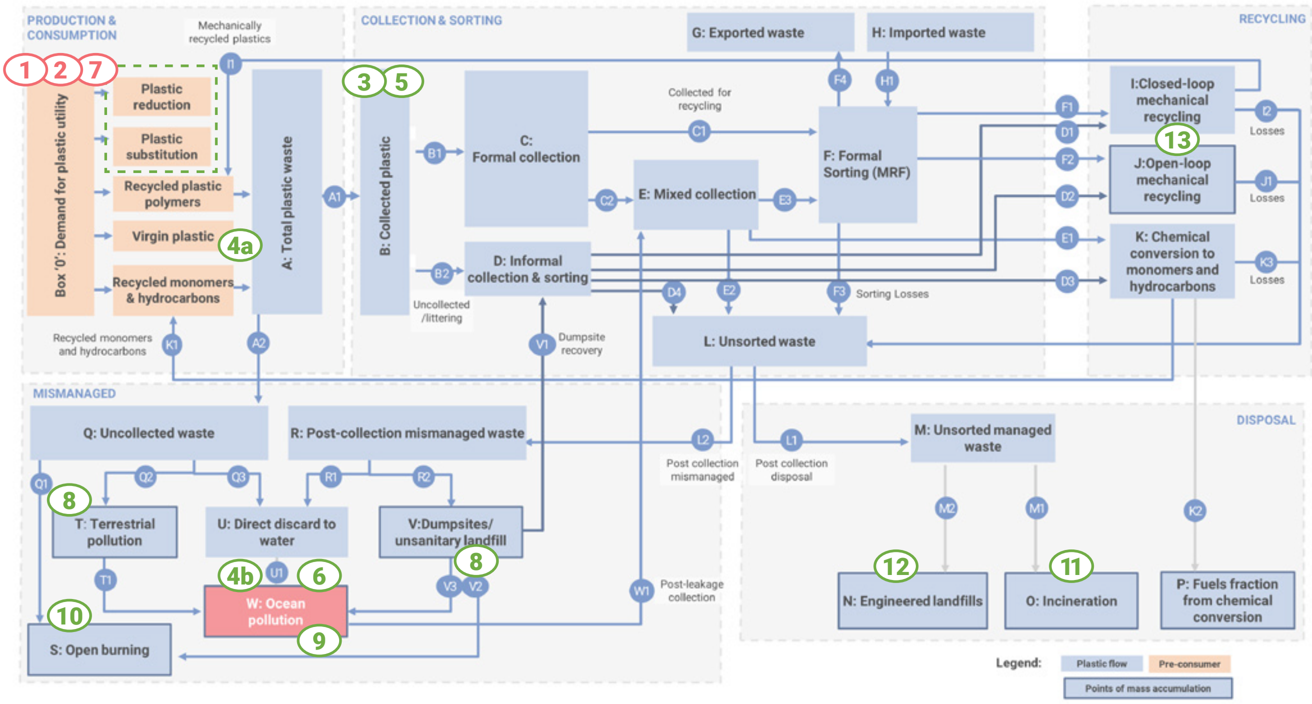

Figure A1.10: **Global plastics system map with GHG and plastic flows for which economic cost coefficients have been used in this study.**

1.2.2 **Cost coefficients used in this study**

The coefficients identified for this assessment consider GHG emissions and air pollution resulting over the life cycle of plastic, the need to clean up plastic that is emitted into the ocean, damages to marine ecosystem services and tourism as well as the exposure to hazardous chemicals in the plastics life cycle. The following paragraphs present the method and coefficients used.

The social costs of carbon (coefficient 1) resulting over the life cycle of plastics is calculated using a low and a high end coefficient of USD 50 and USD 100 per ton of plastic produced (Bond *et al.* 2020, Benham, Vaughan and Chau 2020). A range is applied for this cost indicator to ensure that uncertainties concerning the costs are covered, and given that there is no consensus in the scientific community what the real cost per ton of carbon emissions should be. The authors use prices published by the U.S. Environmental Protection Agency in 2020, whereby the cost per ton of CO_2 range from between USD 93 per ton in the United Kingdom of Great Britain & Northern Ireland to USD 200 per ton in Germany.

The cost of air pollution is estimated using an estimate of the health costs of fossil fuel-based air pollution published by the Center for Research on Energy and Clean Air (CREA). According to CREA (2020), the health costs related to fossil fuel-based air pollution are around USD 2.9 trillion per year, which, if divided by the total CO_2 emissions generated by the energy sector, averages around USD 90 per ton of CO_2 emitted. Bond *et al.* (2020) argue that, given that this falls into the range of the USD 50 to USD 100 per ton of CO_2 assumed for the Social Cost of Carbon, and in absence of a study that estimates the cost of pollution related to the plastics value chain, the same range can be applied to the cost of air pollution.

This study uses the same approach and hence values the cost of air pollution at between USD 250 and USD 500 per ton of plastic produced.

When it comes to estimating the clean-up cost of plastic pollution in the ocean (coefficients 4a and 4b), the costs presented by Bond *et al.* (2020) are based on a 2014 UNEP study that indicated the cost of plastic in the ocean (clean-up) is around USD 13 billion per year (UNEP, 2014), while later studies put this cost at USD 1,500 billion (Forrest *et al.* 2019) and USD 500 to USD 2,500 billion (Beaumont *et al.* 2019) respectively. Departing from the UNEP estimate, and acknowledging that the real cost is likely higher, the value per ton of plastic in the ocean to be cleaned up was estimated at USD 54 and USD 109 respectively. If a capitalization period of 20 and 40 years respectively is applied, the average cost for every new ton of plastic entering the ocean ranges from USD 1,700 per ton to USD 3,400 per ton respectively[7]. Using the global values provided in a study on the cost of river plastic performed by Deloitte, each ton of plastic entering waterways (coefficient 8) has caused between USD 7,040 and USD 7,500 in economic damages to coastal countries in 2018 (Deloitte 2019). This figure includes losses (foregone revenues) to marine tourism, aquaculture producers and fisheries, as well as clean-up costs for governments.

In addition to the clean-up costs and potentially foregone revenues from ocean-dependent sectors, plastic waste disposed in the ocean also causes damages to marine life and depreciates ecosystem services provided by nature. A report published by the World Wildlife Fund for Nature (WWF) provides a price tag for the 2019 cost of plastics to marine ecosystem services (WWF 2021). According to this report, the median pollution cost to marine ecosystem services attributable to the plastic produced in 2019 totals USD 3.1 trillion, with a range from USD 2.1 trillion to USD 4.3 trillion. Averaged over the total tons of plastic produced in 2019 (368 MMt), this results in an average cost between USD 5,707 and USD 11,685 per ton of plastic produced. Beaumont *et al.* (2019) put the average cost to marine capital at between USD 3,000 and USD 33,000 per ton of plastic in the sea (USD 2011 prices).

Atabay *et al.* (2022) have conducted a cradle-to-grave life cycle assessment of plastics and performed a techno-economic analysis for two types of plastics at the town, city and province scale. The two types of plastic analysed are polypropylene and polylactic acid. The assessment focused on the end-of-life management cost of plastics (by type of management technology) and the toxic cost, whereby the values for the highest level of analysis (province scale) were used for this study. Given that the end-of-life management cost are already estimated by the model developed for this study, only the coefficients related to exposure to hazardous chemicals per ton of plastics disposed (by type of end-of-life management technology) were used. The incineration of plastic releases Polycyclic Aromatic Hydrocarbons (PAHs), and the assumption on the valuation of the damage related to exposure to hazardous chemicals caused at province level is USD 685 per kg PAH emitted[8].

For the landfilling of plastics, the authors considered the dioxins absorbed through microplastics in coastal cities, whereby the toxic cost per kilogram of dioxins and furans (poly-chlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F)) is assumed at USD 550 million per kilogram, based on (Martinez-Sanchez *et al.* 2017)[9]. This results in an economic valuation of USD 16,500 per ton of micro plastic waste emitted, as found in Atabay *et al.* (2022). In our assessment we consider the following sources of microplastics: tire abrasion, textiles, pellets and personal care products. Using the same cost per kilogram of dioxins from (Martinez-Sanchez *et al.* 2017), new coefficients were calculated for open-burning of plastics considering the emission factors for PCDD/F from open-burning of clean HDPE (Table 5 in Zhang *et al.* 2017) of USD 322 per metric ton of plastic burnt in the open, added to USD 165 per metric ton for other air emissions from open burning (Atabay *et al.* 2022). A similar process was used to estimate a cost linked to dioxins emitted in fires on dumpsites based on emission estimates from UNEP (2012), at USD 180 per metric ton of plastic waste dumped. Emission of dioxins is also usually linked to incineration of plastic waste; however, emission rates are usually much lower with new technology and emissions control equipment than in the two previous cases of uncontrolled combustion, due to much higher combustion temperature and faster cooling of fumes. Based on emission rates reported in Nzihou *et al.* (2012) and Cheng and Hu (2010), and the cost per kilogram of dioxins above, the expected costs of exposure to dioxins and furans from incineration are a few orders of magnitude lower (0.05-0.95 USD per metric ton of plastic incinerated) and do not affect the overall results of exposure to hazardous chemicals in this study.

[7] This cost figure of USD 54 to USD 109 per ton was estimated based on the 150 MT of plastics that had accumulated in the oceans by 2014. A capitalization period is assumed based on the assumption that plastics entering the oceans will cause damages over the years, unless cleaned up. It should be noted, however, that the cost is difficult to estimate, given that the aggregate value of clean-up costs is estimated based on the stock of plastic, and hence should decline as soon as the stock of plastic declines. A flow-based estimate would be a more appropriate way to estimate the cost of clean-up.

[8] The modeling performed assumes $3.6*10^{-4}$ kg per kg of PP incinerated and $1.2*10^{-4}$ kg per kg PLA incinerated.

[9] The leakage rate of dioxin like compounds at province level is assumed at $3*10^{-8}$ kg with PCDD/F per kg of microplastic.

Table A1.4: **Summary of the coefficients used in the study. The numerical values consider adjustments for inflation and are therefore expresses in constant terms (inflation adjusted), making so that all values are presented in USD2020 (USD with 2020 base year).**

	Indicator	Unit of measure	Lower bound estimate	Upper bound estimate	Reference	Considered in the analysis of externalities?
1	Carbon dioxide	USD/Ton	50 per ton of CO_2	100 per ton of CO_2	Bond *et al.* 2020	X
2	Air pollution	USD/Ton	250	500	Bond *et al.* 2020	X
3	Collection and sorting	USD/Ton	245	327	Bond *et al.* 2020	No, already considered in the material flow analysis
4a	Ocean clean-up (per ton produced)	USD/Ton	58	118	Bond *et al.* 2020	No, double counting with 4b
4b	Ocean clean-up (per ton disposed in water)	USD/Ton	1,838	3,676	UNEP 2014	X
5	Waste management costs	USD/Ton	87	87	WWF 2021	No, already considered in the material flow analysis
6	Ecosystem service costs of marine ecosystem services	USD/Ton	5,749	11,771	WWF 2021	X
7	Cost of the lifetime GHG	USD/Ton	465	465	WWF 2021	No, double counting with 1
8	Average cost per ton of land-sourced plastic waste	USD/Ton	7,269		Deloitte 2019	No, already considered in the material flow analysis
	Exposure to hazardous chemicals – dumpsite	USD/Ton	180		UNEP 2012; Martínez-Sánchez *et al.* 2017	x
9	Ecosystem service costs of marine ecosystem services	USD/Ton	3,000	33,000	Beaumont *et al.* 2019	No, double counting with 6
10	Exposure to hazardous chemicals - open burning	USD/Ton	487		Martínez-Sánchez *et al.* 2017; Zhang *et al.* 2017; Smeaton 2021; Atabay *et al.* 2022	x
11	Exposure to hazardous chemicals – incineration	USD/Ton	0.05	0.95	Cheng and Hu 2010; Nzihou *et al.* 2012	x
12	Exposure to hazardous chemicals - microplastics	USD/Ton	16,500		Atabay *et al.* 2022	x

The coefficients for the valuation of externalities used for this study are highly aggregated, many obtained from assessments at the global level. This is because the impacts of plastic pollution are, to a large extent, specific to regional conditions with respective impacts. Therefore the cost estimates are used for comparative purposes in the absence of more comprehensive costs assessments across the plastics value chain, and will benefit from further refinement. On the other hand, given that for instance ocean plastic pollution is a global problem, it is difficult to further detail some of the cost coefficients used for this study. For instance, the damages to marine capital are a function of damages caused by plastic pollution to the environment, marine animals entangled in plastic waste or killed by fishing gear left out in the ocean (with impacts on reproduction), impacts on the scenic beauty of the environment and its encroaching impacts on the attractiveness of affected beaches/seascapes to tourists and more.

Krelling *et al.* (2017) analysed the differences in perception of the attractiveness of two subtropical beaches caused by marine litter and potential indications on tourism revenues. Depending on the density of plastic waste per m² of beach, in the worst case, up to 85 per cent of beach goers would consider going to another destination. The study reports that marine debris has the potential to lead to a 39.1 per cent reduction in local tourism revenues, which would be equivalent to USD 8.5 million in annual foregone tourism revenues. Qiang *et al.* (2019) developed a theoretical model in which they explored the impact of marine debris on the length of stay for tourists along the East China Sea. They found a statistically significant negative impact of marine litter on tourism revenues and indicate that cleaning up the beaches could increase tourism revenue by between 29 per cent and 32 per cent.

In addition to the reduction in attractiveness of beaches, marine litter at sea causes additional hardship for fishermen and fishing operations. According to Hermawan *et al.* (2017), plastic pollution severely impacts the Selayar fishermen, with additional vessel repair costs of Indonesian Rupiah (IDR) 192.9 million per year and IDR 156.2 million in additional gear repair costs.

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1.2.3 **Results of the economic analysis**

The cumulative (2016-2040) results of applying the coefficients described above to the flows of plastic waste and related emissions modelled in the study are shown in Table A1.5, below; these are the values that inform Figure 5 in the main report.

Table A1.5: **Total system costs for short-lived plastics for the business-as-usual and systems change scenarios.**

Cumulative (2016-2040), USD trillion (in constant 2020 USD)	**Business-as-usual scenario**	**Systems change scenario**
Total opex	$ 9.89	$ 9.96
Total capex	$ 2.83	$ 1.64
Total revenues	$ (0.44)	$ (0.58)
Total Direct Costs	**$ 12.28**	**$ 11.02**
Carbon dioxide	$ 1.97	$ 1.73
Air pollution	$ 1.00	$ 0.75
Ocean clean-up	$ 0.03	$ 0.01
Marine ecosystem services	$ 2.56	$ 1.23
Exposure to hazardous chemicals	$ 4.45	$ 3.03
Total Indirect Costs	**$ 10.00**	**$ 6.75**
OVERALL TOTAL	**$ 22.29**	**$ 17.77**

The evolution of total system costs changes significantly over time, as shown in Figure 6 of the main report. This is illustrated in Table A1.6 below, with the detailed costs in 2016, 2020 and an average year in the period 2016-2040, the latter for both business-as-usual and systems change scenarios.

Table A1.6: **Total annual system costs for short-lived plastics for 2016, 2020 and the average from 2016 to 2040 of the BAU and systems change scenarios (in constant 2020 USD billion).**

Bn USD/year	**2016**		**2020**		**Average 2016 - 2040**			
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
	BAU	**BAU**	**BAU**	**BAU**	**BAU**	**BAU**	**SC**	**SC**
Total opex	400.5	400.5	419.6	419.6	395.7	395.7	398.3	398.3
Total capex	-	-	138.9	138.9	113.2	113.2	65.6	65.6
Recycling revenues	(18.8)	(18.8)	(19.3)	(19.3)	(17.6)	(17.6)	(23.3)	(23.3)
Carbon dioxide	52.0	104.0	60.5	121.1	78.8	157.6	69.3	138.6
Air pollution	27.3	54.5	31.3	62.5	39.9	79.9	30.2	60.3
Ocean cleanup	0.6	1.2	0.7	1.4	1.0	2.1	0.5	1.0
Marine ecosystem services	56.2	115.1	70.2	143.7	102.3	209.5	49.0	100.4
Exposure to hazardous chemicals	109.1	109.1	130.8	130.8	178.2	178.2	121.1	121.1
Externalities	**245.1**	**393.8**	**293.4**	**459.5**	**400.2**	**627.2**	**270.1**	**421.5**
Total	**626.9**	**775.6**	**832.7**	**998.8**	**891.6**	**1,118.6**	**710.8**	**912.1**

1.2.4 **Effects of discounting**

The costs assessed in this analysis are estimated using 2020 as base year. To ensure comparability, an adjustment factor has been used to ensure consistency with the estimation of direct costs and benefits (e.g. capex and opex), which are first estimated in nominal values. This adjustment factor, representing annual inflation, is set at 3.5 per cent.

In the presentation of the results in the main report , a rate of inflation of 3.5 per cent is assumed over the modelling period and used to keep values constant in 2020 dollars. As inflation is likely to taper off, no further discounting is applied in the base scenario. However for completeness, the analysis includes assessing the impact of using different assumptions on discounting: (i) two scenarios where an additional one per cent and three per cent social rate of discount is considered on top of the 3.5 per cent inflation rate, for all direct and indirect costs; and (ii) two more where the additional one per cent and three per cent social rate of discount is applied only to direct costs and benefits, but not to the economic valuation of externalities.

The choice of the discount rate is consistent with ranges found in the literature, with three per cent being the most accepted value (see Broughel 2020 and Drupp *et al.* 2015).

Table A1.7 shows that, in the base case when additional discounting is not applied the systems change scenario results in USD 1.27 trillion in savings considering investment, operations and management costs and additional revenues, and in USD 3.25 trillion savings from avoided externalities. The total value adds up to USD 4.52 trillion (20.3 per cent reduction overall). When adding an additional one per cent discount rate, the avoided costs reach instead USD 4.04 trillion (19.4 per cent reduction), and decline further to USD 3.27 trillion (17.9 per cent reduction) when using three per cent discount rate instead. When considering one per cent discounting only for direct costs and benefits, the savings add up to USD 4.4 trillion (20.4 per cent reduction) and decline to USD 4.21 trillion (20.7 per cent reduction) when increasing the discounting only for direct costs and benefits to three per cent.

Table A1.7: **Impact of using different discount rates on the cost reduction in the BAU versus the systems change scenarios (in constant 2020 USD billion).**

	Only inflation (3.5%)	**Inflation (3.5%) and 1% discounting** (all costs)	**Inflation (3.5%) and 3% discounting** (all costs)	**Inflation (3.5%) and 1% discounting** (direct costs only)	**Inflation (3.5%) and 3% discounting** (direct costs only)
Net change direct costs	$ 1,267.02	$ 1,149.95	$ 958.03	$ 1,149.95	$ 958.03
Net change externalities	$ 3,253.54	$ 2,892.93	$ 2,310.77	$ 3,253.54	$ 3,253.54
Net change (total)	$ 4,520.56	$ 4,042.88	$ 3,268.80	$ 4,403.48	$ 4,211.57
Cost reduction	-20.3%	-19.4%	-17.9%	-20.4%	-20.7%

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