Designing a Circular Carbon and Plastics Economy for a Sustainable Future

Supplementary Information

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1.0 Supporting Materials for Modelled Scenarios of the Plastic Industry in 2050

This perspective aims to propose actions that will reduce CO_2 emissions to net zero by 2050, within the plastic system. To accomplish this, published lifecycle emissions of current petrochemical plastics and their potential substitutes by bio-based alternatives were assessed and compared. The data was used to estimate the effect of different interventions including: 1) reduce plastic demand; 2) switch to renewable raw materials for plastic production (avoid petrochemicals); 3) maximize recycling, and 4) apply renewable energy to all processes. The goal of the scenarios is to highlight the potential collective impacts of such mitigation strategies, and importance of deploying them at scale. It is essential to emphasise that although output CO_2 emissions are quantified in each scenario, the values are not intended to be binding but rather are illustrative to guide the future developments. It is also important to note that the scenarios represent possible outcomes in 2050, rather than a precise forecast. Finally, these emission scenarios do not attempt to quantify or even address other environmental burdens, which otherwise require careful consideration and minimisation, as discussed in the main text.

1.1 Underlying data

This document provides additional data to support the main text, figures and schemes. The large majority of the data used in the present calculations are only available from single sources which do not provide measures of statistical uncertainty on individual values. We, therefore, do not attempt to provide uncertainties on our final calculations (e.g., polymer production, polymer application sectors, and polymer emissions at each life-cycle stage), but note they are likely to be significant, and realistically at least on the order of 10-20% (at 2σ). We emphasise that the data is used to illustrate the consequences of particular interventions and is not to be used definitive model. This work is not a comprehensive life-cycle analysis.

1.2 Data Estimates on Polymer Production Volumes. Analysis by Type and Application

1.2.1 Petrochemical Plastics

For all the 2050 scenarios for the plastic industry, we first report the total volume of that plastic market by both polymer type and application sector, as provided from various sources, including publicly available reports and published literature. As expected, the global production volumes by plastic type show variance (depending on the data source) but numbers are consistent within +/-5% with respect to the total polymer volume from all the sources (Table S1) [1-4] In the polymer application data, there are also regional/geographical differences (Table S2). [2-5] Comparison of available data sets from Europe, USA and Australia demonstrates reasonable agreement in polymer consumption by type (±15% of each polymer type against total polymer volume) in major north and south developed economies. In constructing the scenarios, we assumed a global market sector distributions that follows the market share for the EU27+UK+CH+NO, as reported by the Plastics – The Facts 2021 (Tables S3-4), and scaled to the estimated total sector growth predicted by 2050 (Tables S5-6). [3,6] This data set was selected as it is open access, most recent, and comprehensive. We acknowledge that these sources cover only developed regions and economies and the risks associated with scaling such data. We note that there were not any consistent and comprehensive global plastics consumption datasets or sources which quantify polymer use by sector. Such data collection should be prioritized in future and made openly available to improve future models/scenarios.

Using the available data, the current petrochemical plastics are sorted by the ‘top-7 plastics by volume’, i.e. high density polyethyene (HDPE), linear low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PUR), polyethylene terephthalate (PET). The remaining, specialty polymers (e.g. fluoro-, oxygenates, vinyl resins) are classed as ‘others’. The scenarios assume uniform growth in all sectors by 2050, reaching a total of 1.1 Gt of plastics. [6,7] No account is made for additives in plastics since these are typically much lower volumes and information is lacking on these materials.

1.2.2 Renewable Plastics

In terms of renewably sourced plastics, there are some examples of industrialised bio-based plastics but production volumes remain <1% of the total market in 2020. [8] In selecting the renewable plastics, 5 examples were chosen as representative of both ‘drop in’ and ‘new’ polymers: bio-polyethylene (bio-PE), bio-polyethylene terephthalate (bio-PET), polylactic acid (PLA), polyhydroxyalkanoates (PHA), and thermoplastic starches (TPS). These were identified by others as good exemplars of the current and future bio-based polymer industry, but are not necessary representative of future polymers derived from carbon capture and utilization technologies. [8] The potential of these, and other, renewable plastics to substitute petrochemical plastics was also identified, and in the 2050 scenarios we employ the same substitution factors as previously tabulated. Finally, it is important to emphasize that any projections of material substitution by current bio-based plastics cannot account for future developments that could provide better alternatives. For the purpose of these modelling scenarios, renewable plastics are classified as:

- **Drop-in plastics** are direct replacements for petrochemical plastics (they have the same chemical structure), but are derived from alternative resources. When drop-in plastics are non-biodegradable, the same end-of-life treatment options are expected as with traditional petrochemical-based plastics. Here, bio-PE and bio-PET are exemplars of drop-in plastics.
- **Biodegradable plastics** are synthetic alternatives to petrochemical plastics that are derived from biomass, or CCU, and can be biodegradable or compostable. Thus, in the scenarios PLA, PHA, and TPS are exemplars of biodegradable polymers.

1.3 Definition of Scenarios

All of the scenarios are outlined in Table S9. Here is a summary of their rationale.

- **Baseline:** The baseline scenario defines the worst outcome for the plastic industry in terms of carbon recirculation and GHG emissions, i.e., the scenario where plastic consumption reaches the expected levels without any attempted environmental remediation, featuring no recycling or further development of a renewable energy sector. In this scenario, all plastics are produced from fossil resources, and disposed of by landfilling (70%) and incineration (30%).

- **Business-as-Usual (BAU):** The BAU scenario represents a linear projection of current lifecycles and end-life treatments to 2050. It assumes linear growth of plastic demand per year to 1.1 Gt, but factors in an increase in recycling (43%) and incineration rates (50%), and a decline in use of landfill (7%), as predicted by Geyer.[6,7] In the BAU, it is assumed that recycled plastics account for ~39% of raw material demand for future plastics. In this scenario there is no significant implementation of bio-based plastics, or use of renewable resources or carbon dioxide utilization.
- **Conservative commitments scenario (CCS):** This scenario illustrates the effects of a series of barriers that prevent the full-scale implementation of key actions (see main text). For instance, due to inadequate access to waste collection across different geographies, it is expected that on current trajectory, up to 60% of plastic waste will be mismanaged by 2050.[9,i] As such, this scenario assumes a maximum recycling rate of 40% while the rest of the waste is lost to the economy. Of this unrecycled waste, petrochemical and 'drop-in' plastics are incinerated, and bio-based plastics are degraded (with data from industrial composting used to project emissions impacts). These assumptions reflects the worst-case CO_2-GHG emissions for these plastics, with the data for incineration being the closest related EOL option to predict impacts of the open-burning of mismanaged plastic and industrial composting allowing for impacts to be estimated for discarded biodegradable waste. The open-burning and discarding options are relevant to some rural areas and developing economies. This system uses an equal mixture of the current energy grid and renewable energy, 50% bio-derived raw material use and 75% plastic consumption reduction.
- **Bold-System-Change (BSC):** In this scenario, all the interventions are adopted globally as outlined in the main manuscript. This system uses a "decarbonized" energy grid, uses only bio-derived plastics, with a consumption rate of 50% vs. BAU. At the end-of-life stage, 95% of plastic waste is collected for recycling while the other 5% is lost to the environment through bio-degradation or incineration.

1.4 Data on Lifecycle Emissions

With the projected volume of the plastic industry in 2050, the lifecycle GHG emissions of each plastic type were estimated. In producing such estimates, a modified version of the method reported by Zheng and co-workers was applied.[8] In this method the overall volumes of plastics produced are multiplied by the estimated lifecycle GHG emissions according to the relationship:

$$GHG_s = \sum Q_{s,j} \times E_{s,i,j,k} \times R_{s,j,k}$$

[i] Lack of infrastructure in many parts of the world creates a 'collection gap' which places hard limits on the supply of plastic material for further processing, and likely constrains the economics of a potentially circular system. Globally, approximately 500,000 people need to be connected to waste collection infrastructure each day over the coming decades to meet this challenge under BAU.[9] These issues are felt acutely in more rural parts of the developing world, but also affect adjacent urban areas. Reduction of plastic use and investment in infrastructure (both formal and informal) will improve this picture, but the practicalities of collection will inevitably place limits on the pace at which circularity can be achieved at global scales.

where $Q_{s,j}$ represents the annual global production of plastic of type *j* under scenario *s*; $E_{s,i,j,k}$ represents the per-unit weight emissions of GHG *i* (kg CO_2-eq/kg polymer) by plastics type *j*, at its lifecycle stage *k*, under scenario *s; and* $R_{s,i,j,k}$ is a rate modifier from 0-1 that describes the expected scaling applied by plastic type *j*, at its lifecycle stage *k*, as described for each scenario *s*. The lifecycle stages were divided by upstream (manufacturing) and downstream (end-of-life management options) processes, not accounting for the carbon emissions resulting during the use phase. Values of *E* (per weight emissions) were estimated making use of data sources as described below.

1.4.1 Manufacturing

Encompasses the emissions contributions from two processes: virgin plastic production and conversion, with data sets being reported by Beckham and Suh, respectively. [4,8] In estimating the emissions data, the weight averaged GHG emissions (kg CO_2-eq/kg polymer) per polymer type were multiplied by the estimated global annual consumption. Where data were available for multiple subclasses of polymer types (e.g., for various grades of high density and low density polyethylene), and they were combined to obtain the weight averaged GHG emissions, *E*. Upstream emissions from those data sources take account of usage of: electricity and other utilities, fossil feedstock extraction, fossil feedstock transportation, petrochemical refining and transportation, monomer and precursors, and commodity polymers.

1.4.2 End-of-Life (EoL)

Encompasses the emissions contributions from landfilling, incineration, recycling, industrial composting, and anaerobic digestion. This data was used from the values reported by Suh. [8] It only considers the current state of development of these technologies, i.e. there is no consideration of any future improvements. For instance, chemical recycling is still in its infancy, and while it is expected to play a significant role in future recycling, its contribution to current projections is not accounted for. As technologies evolve, reporting of their associated carbon emissions by plastic type should be compared with mature technologies such as mechanical recycling or industrial composting.

1.5 Energy Grids

Sources of energy have a direct impact on the carbon footprint of a given process, and thus the differences between the current energy infrastructure and a future decarbonized energy system have important impacts on future GHG emissions. An extrapolation of today’s energy mix to 2050 provides an estimate of GHG emissions if no further actions are taken, which is considered in the baseline and BAU scenarios. In contrast, the bold system change scenario assumes a fully electrified energy grid from renewable resources. A mid-point interpolation between the two energy systems serves as the estimate for the incomplete deployment of the renewable energy grid in the conservative commitment scenario. Again, it must be emphasized that this data might be re-evaluated in future when process efficiencies evolve, particularly with further developments in renewable energy.

1.5.1 Current Energy Infrastructure

CO_2 emissions for polymer production in 2050 assuming the current energy grid were taken from the recent report by Beckham *et al*, the work applies the 2018 US grid energy composition in its models (Table S7). [4,10] The USA gross electricity energy production was based on data from the U.S. Energy Information Administration, 2018: 13.1% coal, 36.9% oil, 31.2% natural gas, 8.4% nuclear, 11.2% renewables (further breakdown of renewables not given). The range of polymer end-of-life pathways and CO_2 emissions using the current energy grid in 2050 are taken from the recent report by Suh *et al* (Table S7). [8] The work applies the 2016 global energy composition in its models. [11] The global gross electricity energy production by the International Energy Agency, 2016: 38.3% coal, 3.7% oil, 23.1% natural gas, 10.4% nuclear, 16.6% hydro, 2.3% biomass, and 5.6% solar/wind/geothermal/others.

1.5.2 'Decarbonized' Energy Infrastructure

The decarbonized energy grid in 2050 (i.e. 100% renewable energy) was modelled in the recent report of Suh *et al* which used data adapted from the works of Griffin and Heath.[8,12,13] The dataset estimates electricity generation using 100% wind energy and heat from 100% biogas, using 49 global references, see papers for further details. This dataset was applied in all energy estimates in the bold system change scenario (Table S8).

1.6 Model Levers: Construction of the Future Plastics Industry Scenarios

The four scenarios of the plastics industry in 2050 are constructed by parametrization of key levers that determine the GHG emissions for each scenario. These are given in Table S9, and are described below:

1) **Plastic Consumption Reduction.** This parameter defines the percentage of the plastic share which has been removed through interventions from the baseline volume of plastics produced in 2050 (1.1 Gt). This intervention results in an overall reduction of the volume of plastic across all lifecycle stages, thus having a direct impact on GHG emissions. The baseline and BAU scenarios assume no reduction in plastic demand (0%), while conservative commitments and bold system change assume specific degrees of plastic consumption reduction.
2) **Virgin Plastic Production.** This parameter defines the percentage of the baseline volume produced in 2050 (1.1 Gt) obtained from non-recycled resources, i.e., requiring new raw materials to obtain virgin polymers. The recycling efficiency in the datasets is 90% in all scenarios, i.e., for 100 Mt of plastic recycled, the maximum recovery of recyclate is 90 Mt and the remaining 10 Mt would have to be produced from cradle. This ambitious assumption considers that 100% recycling efficiency is unfeasible due to polymer degradation, loss of material quality after recycling, and overall material losses during reprocessing. As virgin plastic consumption reduces and recycling increases, the amount of virgin plastic produced diminishes.

3) **Bio-based plastic uptake.** This parameter defines the percentage of the plastic share which is comprised of bio-based plastics.
4) **Conversion.** This parameter reflects the transformation of unprocessed plastics into final products. These unprocessed plastics are obtained from recycled resources (90% of the recycled stream) plus a small quantity (10%) of virgin plastics, and must meet the demand required to satisfy the expected growth in the economy in 2050.
5) **End-of-Life Treatment Options**. This parameter defines the specific fate of plastics, by percentage, between landfill, incineration, recycling, anaerobic digestion and aerobic composting.
6) **Grid Energy System**. Three different grid energy types are considered: a grid based on the current energy infrastructure, one which uses only fully decarbonized energy, or a mid-point interpolation between today/fully renewable to reflect an intermediate deployment of renewable energy (50% contribution of current energy mix, and 50% contribution of decarbonized energy).

1.7 The Lifespan and Recoverability of Different Plastics Classes

Using the smart design principles outlined in Box 2. of the main manuscript, the management of four exemplar classes of plastic were compared in the business-as-usual and bold system change scenarios to estimate the annual virgin production and associated lifecycle emissions (Figure 3B, Tables S12-16). The goal is to match the system levers (section 1.6) with particular lifecycle decisions based on their taxonomy (as judged by their application lifespan and recoverability), so as to minimizes the environmental impacts of these plastic products. In all cases, an expected demand reduction of 50% is accounted for in the bold system change scenario.

1) **Highly recoverable, short lifespan materials** are represented by retrievable packaging (Table S13). In the bold system change scenario, smart design determines that these products should be produced from renewable resources and, at their EoL, collected and recycled. This implies that design decisions must be taken to improve their recyclability. It is estimated that 67% of plastic packaging can be recycled and we classify it as recoverable packaging, hence we use these market shares to estimate the proportion of future retrievable packaing.[14]
2) **Low recoverable, short lifespan materials** are represented by complex packaging (Table S14). These products are typically made of multi-layer materials, or are heavily contaminated, making their recycling very difficult. In the bold system change scenario, these plastics should be produced from renewable resources; however, any substitution by drop-in polymers will face similar challenges to be recycled and will require landfilling or incineration. It is therefore important to re-design these materials to improve their recyclability, or substitute them by alternative materials that can be degraded. All renewable plastics that are also degradable must be treated under controlled conditions (for instance, in industrial composting facilities) if they cannot be recycled. It is estimated that at least 33% of plastic packaging cannot be recycled, e.g. multi-layered materials, hence this figure is used to estimate the options for future “complex packaging”.[14]
3) **Highly recoverable, long lifespan materials** are represented by construction products, such as piping and window frames (Table S15). These materials need durability to impart their function over a long period of time, but they should be

equally collected at their EoL. In the bold system change scenario, these plastics should be produced from renewable resources, and recycled.

4) **Low recoverable, long lifespan materials** are represented by agriculture products, such as mulch films (Table S16). These materials need some durability to impart their function, but their application also prevents recycling. In the bold system change scenario, these materials should be fully biodegradable and have minimal adverse environmental effects when employed.

2.0 GHG Emissions Calculations and Assumptions

2.1 Production of Polymers by type

Table S1: Estimated Global Production of Polymers by Quantity.

Source	The Life Cycle of Plastics[1]	Plastics – The Facts 2022[2]	Beckham *et al*[4]
Year Published	2021	2022	2021
Year Estimated	2018	2021	2016-2019
Polymer		Global Production (MMT per year)	
HDPE	43.4	48.9	46.1
LDPE	62.3	56.2	46.0
PP	67.9	75.4	52.6
PS	25.5	20.1	28.7
PVC	37.3	50.4	45.6
PUR	26.6	21.5	16.3
PET	24.7	24.2	62.3
Other	70.7	94.0	81.0
Total	359	391	379

Table S2: Estimated Regional Consumption of Polymers by Quantity.

Source	Hossain *et al*[5]	Plastics – The Facts 2021 and 2022[2,3]		Beckham *et al*[4]
Year Published	2021	2021 and 2022		2021
Year Estimated	2018	2020 and 2021		2016-2019
Region	Australia	EU27+UK+CH+NO		USA
Polymer		Regional Consumption (MMT per year)		
HDPE	0.76	6.3	5.3	6.7
LDPE	0.44	8.6	8.4	4.1
PP	0.57	9.7	9.5	6.0
PS	0.19	3.0	3.5	2.9
PVC	0.46	4.7	6.5	4.9
PUR	0.11	4.1	3.1	2.3
PET	0.41	3.8	3.0	3.0
Other	0.49	8.9	17.8	8.5
Total	3.43	49.1	57.2	38.4

2.2 Polymer Applications by Sector

Table S3: EU27+UK+CH+NO overall market demand for polymers by type and application sector in 2020 as reported by Plastics – The Facts 2021.[3]

Converters Plastics Demand	Packaging	Construction	Automotive	Electronics	Agriculture	Household, Leisure, Sports	Others	Total
	Consumption (Mt)							
HDPE	3.6	1.4	0.3	0.2	0.0	0.3	0.6	6.3
LDPE	5.9	0.5	0.2	0.3	0.5	0.1	1.2	8.6
PP	4.7	0.8	0.9	0.5	0.5	0.8	1.5	9.7
PS	0.9	1.5	0.1	0.2	0.0	0.2	0.2	3.0
PVC	0.4	3.4	0.2	0.1	0.1	0.2	0.3	4.7
PET	4.1	0.0	0.0	>0.1	>0.1	>0.1	>0.1	4.1
PUR	0.1	1.0	0.6	0.3	0.0	0.0	1.8	3.8
Other	0.3	1.5	2.1	1.5	0.3	0.6	2.7	8.9
Total	19.9	10.1	4.3	3.0	1.6	2.1	8.2	49.1

Table S4: EU27+UK+CH+NO % overall market demand of polymers by application sector and polymer types in 2020, as reported by Plastics – The Facts 2021.[3]

Converters Plastics Demand	Packaging	Construction	Automotive	Electronics	Agriculture	Household, Leisure, Sports	Others	Total
	%							
HDPE	7.3	2.8	0.7	0.3	0.1	0.5	1.1	12.8
LDPE	12.0	0.9	0.3	0.6	1.1	0.1	2.4	17.5
PP	9.5	1.6	1.9	1.0	1.1	1.6	3.0	19.7
PS	1.8	3.1	0.1	0.3	0.0	0.3	0.4	6.1
PVC	0.8	7.0	0.3	0.3	0.3	0.4	0.5	9.6
PET	8.3	0.0	0.0	0.0	0.0	0.0	0.0	8.4
PUR	0.1	2.0	1.2	0.7	0.0	0.1	3.6	7.8
Other	0.7	3.0	4.2	3.0	0.6	1.2	5.6	18.2
Total	40.5	20.5	8.8	6.2	3.2	4.3	16.7	[redacted]

Table S5: Global market demand for polymers by type and application sector 2016-19. [3,4]

Converters Plastics Demand	Packaging	Construction	Automotive	Electronics	Agriculture	Household, Leisure, Sports	Others	Total
	Consumption (MMT)							
HDPE	26.1	10.2	2.4	1.2	0.3	1.8	4.1	46.2
LDPE	31.7	2.5	0.9	1.5	2.8	0.3	6.2	46.0
PP	25.3	4.4	5.1	2.7	2.9	4.2	8.0	52.6
PS	8.2	14.4	0.7	1.6	0.2	1.5	1.9	28.5
PVC	3.9	33.2	1.5	1.3	1.4	1.8	2.6	45.6
PET	61.7	0.0	0.0	0.2	0.2	0.2	0.2	62.3
PUR	0.2	4.3	2.6	1.4	0.0	0.2	7.7	16.3
Other	2.9	13.3	18.7	13.3	2.6	5.5	24.8	81.0
Total	160.1	68.9	13.2	9.8	7.7	10.1	30.7	378.6

Notes: Determined using for global polymer production from 2016-19 (Table S1 – Beckham *et al*) and an estimated global market share from 2020 (Table S3-S4 – Plastics - the Facts 2021). [3,4]

Table S6: Global market demand of polymer by type and application sector 2050. [7]

Converters Plastics Demand	Packaging	Construction	Automotive	Electronics	Agriculture	Household, Leisure, Sports	Others	Total
	Consumption (MMT)							
HDPE	75.7	29.5	7.0	3.6	0.8	5.3	11.9	133.5
LDPE	92.1	7.2	2.6	4.4	8.2	0.9	18.0	133.8
PP	73.3	12.7	14.8	7.7	8.3	12.3	23.3	152.5
PS	23.7	41.7	1.9	4.7	0.6	4.4	5.5	82.5
PVC	11.3	96.3	4.2	3.7	3.9	5.3	7.6	132.3
PET	179.0	0.0	0.0	0.4	0.4	0.4	0.4	180.7
PUR	0.6	12.4	7.6	4.0	0.0	0.5	22.2	47.2
Other	8.4	38.5	54.3	38.5	7.6	15.8	74.4	237.5
Total	455.7	199.7	38.1	28.4	22.4	29.2	88.9	1100[7]

Notes: Determined using data for total global polymer market demand in 2020 (Table S8) and estimated growth by 2050 (The New Plastics Economy: Rethinking the future of plastics). [7] Assumes uniform growth in all sectors in 2050.

2.3 Polymer Lifecycle Emissions

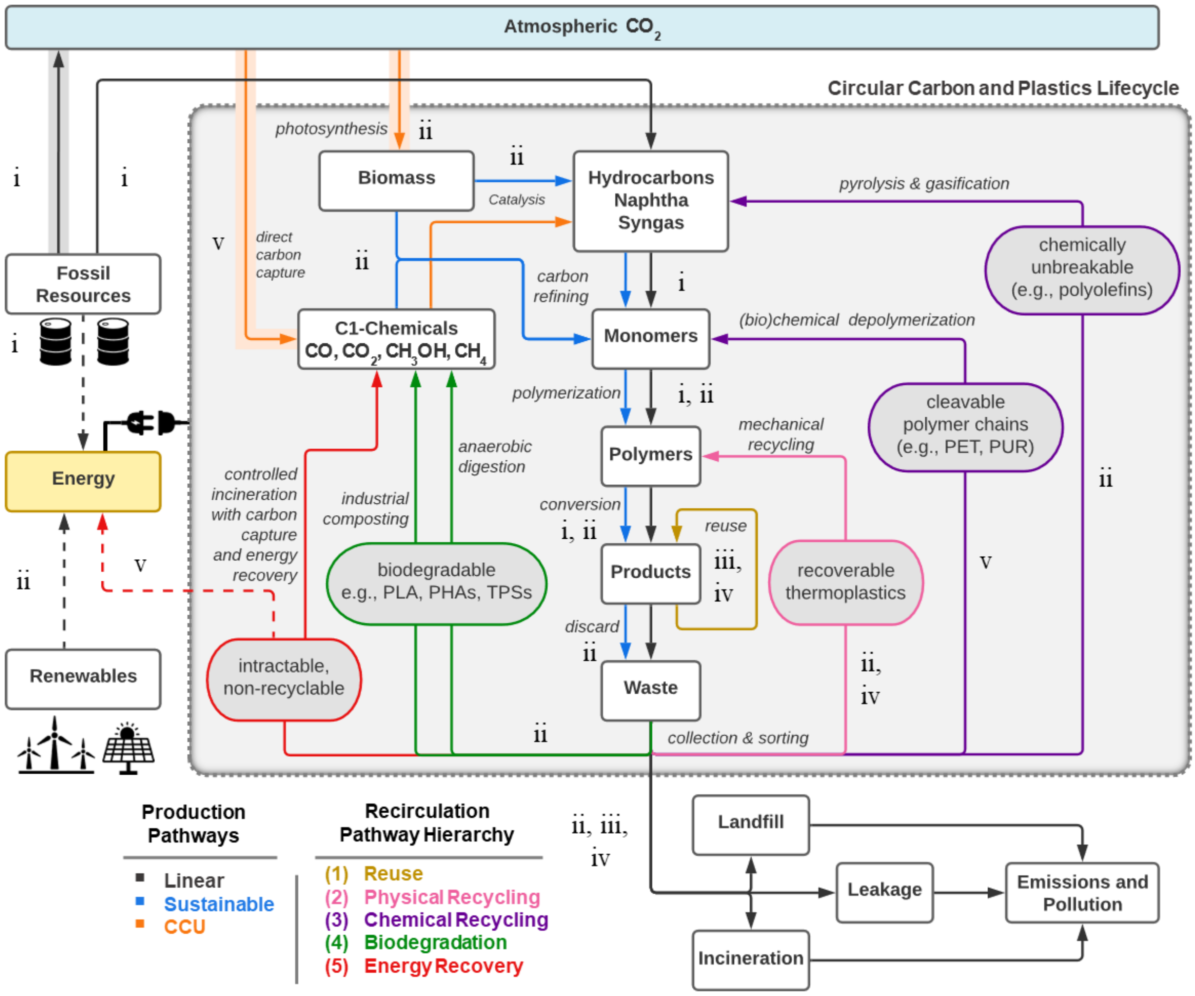

Figure S1: Annotated Circular Carbon and Plastics Lifecycle

(i) Nicholson, S. R., Rorrer, N. A., Carpenter, A. C. & Beckham, G. T. Manufacturing energy and greenhouse gas emissions associated with plastics consumption. Joule 5, 673-686 (2021).[4] (ii) Strategies to reduce the global carbon footprint of plastics. Nat. Clim. Change 9, 374-378 (2019).[8] (iii) Plastics - The Facts 2021.[3] (iv) The New Plastics Economy: Rethinking the future of plastics. https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics (Ellen MacArthur Foundation, 2016)[7] and The New Plastics Economy: Rethinking the future of plastics & catalysing action. https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics-and-catalysing (Ellen MacArthur Foundation, 2022).[14] (v) Not covered in this work.

Table S7: Net GHG emissions of selected polymers (kgCO_2e/kg) under current energy infrastructure.[4,8]

Polymer	Production	Conversion	Landfilling	Incineration	Recycling	Ind. Compost.	Anae. Digestion
HDPE	1.4	1.1	0.1	1.3	0.9	-	-
LDPE	2.0	1.1	0.1	1.3	0.9	-	-
PP	2.0	1.4	0.1	1.3	0.9	-	-
PS	3.5	1.2	0.1	1.3	0.9	-	-
PVC	2.1	0.6	0.1	1.3	0.9	-	-
PUR	4.9	1.2	0.1	1.3	0.9	-	-
PET	3.3	0.8	0.1	1.3	0.9	-	-
Other	2.8	1.0	0.1	1.3	0.9	-	-
Bio-PE	0.8	1.3	0.1	1.3	0.9	-	-
Bio-PET	2.2	1.3	0.1	1.3	0.9	-	-
PLA	1.2	1.3	0.0	1.2	0.9	1.5	0.7
Starch-blends	1.3	1.3	1.3	1.3	0.9	1.4	0.6
PHA	2.7	1.3	3.4	1.3	0.9	1.8	0.8

Notes: Production GHG Emissions for HDPE, LDPE, PP, PS, PVC, PUR and PET, were calculated using literature data.[4] Production GHG Emissions for Others, Bio-PE, Bio-PET, PLA, Starch-blends and PHA were calculated from a second literature data-set.[8] All end-of-life GHG Emissions were calculated using literature data.[8]

Table S8: Net GHG emissions of selected polymers (kgCO2e/kg) in a decarbonized energy scenario[8]

Polymer	Production	Conversion	Landfilling	Incineration	Recycling	Ind. Compost.	Anae. Digestion
HDPE	0.8	0.2	0.1	2.2	0.4	-	-
LDPE	0.8	0.2	0.1	2.2	0.4	-	-
PP	1.1	0.2	0.1	2.2	0.4	-	-
PS	1.9	0.2	0.1	2.2	0.4	-	-
PVC	0.6	0.1	0.1	2.2	0.4	-	-
PUR	2.1	0.2	0.1	2.2	0.4	-	-
PET	1.5	0.1	0.1	2.2	0.4	-	-
Other	1.2	0.1	0.1	2.2	0.4	-	-
Bio-PE	-0.5	0.2	0.1	2.2	0.4	-	-
Bio-PET	0.3	0.2	0.1	2.2	0.4	-	-
PLA	-0.1	0.2	0.0	1.7	0.4	1.7	1.4
Starch-blends	0.3	0.2	1.2	1.9	0.4	1.6	1.3
PHA	1.0	0.2	3.4	1.8	0.4	1.9	1.6

Notes: All GHG Emissions use literature estimates/models. [8]

Table S9: Data and Actions underpinning the 4 Scenarios Illustrated in Figure 2.

Scenarios in 2050	Manufacturing		EoL Treatments Options	Grid Energy System	Plastic Consumption Reduction	Bio-based Plastic uptake
	Virgin Plastic Production	Conversion				
Baseline Scenario	100%	100%	**Petrochemical plastics** • Landfilling 70% • Incineration 30%	100% Current Energy Infrastructure	0%	<1%
Business -as-Usual (BAU)	61%	100%	**Petrochemical plastics** • Landfilling 7% • Incineration 50% • Recycling 43%	100% Current Energy Infrastructure	0%	<1%
Conservative Commitments Scenario (CCS)	48%	75%	**Petrochemicals and drop-in plastics** • Incineration 60% • Recycling 40% **Bio-based new plastics** • Recycling 40% • Industrial Composting 60%	50% Current Energy Infrastructure 50% Decarbonized Energy Infrastructure	25%	50%
Bold System Change (BSC)	7.25%	50%	**Drop-in plastics** • Landfilling 1.5% • Incineration 3.5% • Recycling 95% **Bio-based new plastics** • Industrial Composting 4% • Anaerobic Digestion 1% • Recycling 95%	100% Decarbonized Energy Infrastructure	50%	100%

Table S10: Data, by Share of Plastics, Supporting the Scenarios Illustrated in Figure 2.

Plastics			Baseline		Business-as-Usual		Conservative Commitments		Bold System Change	
			Share (MMT)	GHGe (MMT CO_2-eq.)	Share (MMT)	GHGe (MMT CO_2-eq.)	Share (MMT)	GHGe (MMT CO_2-eq.)	Share (MMT)	GHGe (MMT CO_2-eq.)
Petrochemicals		HDPE	134	473	134	452	50	127	0	0
		LDPE	134	469	134	447	50	126	0	0
		PP	153	581	153	555	57	158	0	0
		PS	83	431	83	368	31	109	0	0
		PVC	132	413	132	386	50	117	0	0
		PUR	47	309	47	248	18	70	0	0
		PET	181	831	181	706	68	208	0	0
		Other	235	1018	235	901	88	283	0	0
Renewable	“drop-in”	Bio-PE	0	0	0	0	129	280	172	47
		Bio-PET	0	0	0	0	37	107	50	16
	biodegra-dable	PLA	1	3	1	4	95	214	127	39
		Starch-blends	1	4	1	4	74	179	98	32
		PHA	~0.1	1	~0.1	1	76	241	102	39
		TOTAL (GT)	1.10	–	1.10	–	0.82	–	0.55	–
		TOTAL (Gt-CO_2-eq.)	–	**4.53**	–	**4.07**	–	**2.22**	–	**0.17**

The total share of a plastic within the system, is the sum of virgin plastic production and virgin-quality plastics produced from recycling.

Table S11: Data, by Lifecycle Stage, Supporting the Scenarios Illustrated in Figure 2.

		Baseline (MMT CO_2-eq.)		Business-as-Usual (MMT CO_2-eq.)		Conservative Commitments Scenario (MMT CO_2-eq.)		Bold-System-Change (MMT CO_2-eq.)	
		Petrochem.	**Renewable**	**Petrochem.**	**Renewable**	**Petrochem.**	**Renewable**	**Petrochem.**	**Renewable**
Manufacturing	Virgin Production	2889	3	1771	2	498	204	0	4
	Conversion	1130	3	1130	4	241	309	0	50
End-of-Life	Landfilling	68	1	7	0	0	0	0	8
	Incineration	436	1	727	1	353	177	0	97
	Recycling	0	0	428	1	105	105	0	11
	Industrial Composting	0	0	0	1	0	242	0	2
	Anaerobic Digestion	0	0	0	0	0	0	0	2
	TOTAL (GT)	4.52	~0.01	4.06	~0.01	1.14	0.96	0	0.17
	TOTAL (Gt-CO_2-eq.)	**4.53**		**4.07**		**2.10**		**0.17**	

2.4 Data Supporting the Quadrants Illustrated in Figure 3

Table S12: Estimated annual virgin production of polymers in 2050 for selected sectors in "Business-as-usual" and "Bold System Change" scenarios.

Category	**Irretrievable and Short-Lived**		**Recoverable and Short-Lived**		**Recoverable and Long-Lived**		**Irretrievable and Long-Lived**	
Example	**Complex Packaging**		**Recoverable Packaging**		**Construction**		**Agriculture**	
Plastic	**Annual Virgin Prod. (Mt), BAU**	**Annual Virgin Prod. (Mt), BSC**	**Annual Virgin Prod. (Mt), BAU**	**Annual Virgin Prod. (Mt), BSC**	**Annual Virgin Prod. (Mt), BAU**	**Annual Virgin Prod. (Mt), BSC**	**Annual Virgin Prod. (Mt), BAU**	**Annual Virgin Prod. (Mt), BSC**
HDPE	24.7	–	30.8	–	18.1	–	1.3	–
LDPE	30.4	–	37.8	–	4.1	–	8.0	–
PP	24.2	–	30.1	–	7.5	–	7.6	–
PS	11.2	–	13.9	–	25.7	–	0.6	–
PVC	3.9	–	4.9	–	59.2	–	4.0	–
PUR	0.2	–	0.2	–	7.5	–	0	–
PET	59.0	–	73.5	–	0.0	–	0	–
Others	3.4	–	2.9	–	22.4	–	8.4	–
Bio-PE	0.0	21.1	0.0	6.2	–	16.2	–	0.0
Bio-PET	0.0	16.2	0.0	4.8	–	0.0	–	0.0
PLA	0.4	19.9	0.0	5.8	–	4.7	–	5.2
Starch-blends	0.4	9.5	0.6	2.8	–	4.9	–	5.2
PHA	0.0	11.7	0.6	3.4	–	5.5	–	4.5
TOTAL (Mt)	157.8	78.5	195.3	22.9	144.4	31.3	29.9	15.0

Table S13: Data Underpinning Figure 3, Recoverable Packaging in 2050.

Plastic category	Life-Cycle Stage	Rate (%), BAU	GHG emissions (MMT CO_2-eq.), BAU	Rate (%), BSC	GHG emissions (MMT CO_2-eq.), BSC
(Virgin) Petrochemical and bio-derived Drop-In Plastics	Virgin Production	61.3	0.507	7.25	-0.001
	Conversion	100	0.325	50	0.014
	Landfilling	7	0.002	1.5	0.000
	Incineration	50	0.210	3.5	0.006
	Recycling	43	0.123	95	0.027
	Ind. Composting	0	0.000	0	0.000
	Anaerobic Digestion	0	0.000	0	0.000
Biodegradable Plastics	Virgin Production	60.4	0.002	50	0.004
	Conversion	100	0.003	50	0.015
	Landfilling	6	0.000	0	0.000
	Incineration	30	0.001	0	0.000
	Recycling	44	0.001	95	0.029
	Ind. Composting	18	0.001	4	0.006
	Anaerobic Digestion	2	0.000	1	0.001
TOTAL			**1.173**		**0.100**

Table S14: Data Underpinning Figure 3, Complex Packaging in 2050.

Plastic category	Life-Cycle Stage	Rate (%), BAU	GHG emissions (MMT CO_2-eq.), BAU	Rate (%), BSC	GHG emissions (MMT CO_2-eq.), BSC
(Virgin) Petrochemical and bio-derived Drop-In Plastics	Virgin Production	100	0.410	50	-0.002
	Conversion	100	0.161	50	0.007
	Landfilling	70	0.010	70	0.000
	Incineration	30	0.062	30	0.003
	Recycling	0	0.000	0	0.013
	Ind. Composting	0	0.000	0	0.000
	Anaerobic Digestion	0	0.000	0	0.000
Biodegradable Plastics	Virgin Production	100	0.001	50	0.013
	Conversion	100	0.001	50	0.008
	Landfilling	70	0.000	0	0.000
	Incineration	30	0.000	0	0.000
	Recycling	0	0.000	0	0.000
	Ind. Composting	0	0.000	90	0.063
	Anaerobic Digestion	0	0.000	10	0.006
TOTAL			**0.646**		**0.111**

Table S15: Data Underpinning Figure 3, Construction in 2050.

Plastic category	Life-Cycle Stage	Rate (%), BAU	GHG emissions (MMT CO_2-eq.), BAU	Rate (%), BSC	GHG emissions (MMT CO_2-eq.), BSC
(Virgin) Petrochemical and bio-derived Drop-In Plastics	Virgin Production	61.3	0.371	7.25	-0.004
	Conversion	100	0.219	50	0.011
	Landfilling	7	0.001	1	0.000
	Incineration	50	0.156	4	0.005
	Recycling	43	0.092	95	0.022
	Ind. Composting	0	0.000	0	0.000
	Anaerobic Digestion	0	0.000	0	0.000
Bio-derived new Plastics	Virgin Production	–	–	7.25	0.004
	Conversion	–	–	50	0.010
	Landfilling	–	–	0	0.000
	Incineration	–	–	0	0.000
	Recycling	–	–	95	0.020
	Ind. Composting	–	–	4	0.004
	Anaerobic Digestion	–	–	1	0.001
TOTAL			**0.839**		**0.073**

Table S16: Data Underpinning Figure 3, Agriculture in 2050.

Plastic category	Life-Cycle Stage	Rate (%), BAU	Life-Cycle CO_2 Emissions (MMT), BAU	Rate (%), BSC	Life-Cycle CO_2 Emissions (MMT), BSC
(Virgin) Petrochemical and bio-derived Drop-In Plastics	Virgin Production	100	0.068	7.25	-0.004
	Conversion	100	0.032	50	0.011
	Landfilling	7	0.002	1	0.000
	Incineration	50	0.012	4	0.005
	Recycling	43	0.000	95	0.022
	Ind. Composting	0	0.000	0	0.000
	Anaerobic Digestion	0	0.000	0	0.000
Bio-derived new Plastics	Virgin Production	–	–	7.25	0.006
	Conversion	–	–	50	0.003
	Landfilling	–	–	0	0.000
	Incineration	–	–	0	0.000
	Recycling	–	–	0	0.000
	Ind. Composting	–	–	90	0.023
	Anaerobic Digestion	–	–	10	0.002
TOTAL			**0.114**		**0.034**

3.0 Supplementary Information of Economic Challenges in Section 3

3.1 Petrochemical Investment and Carbon Lock-In Risk

Globally the petrochemical industry has/will invest an estimated $400 billion, between 2020-2025, in new petrochemical facilities.[15] These investments are frequently tracked and discussed in financial and chemical industry news media in relation to the ways in which they are dependent on and assume the perpetuation of fossil-fuel based plastics. It is estimated that 45% (IEA) to 95% (BP) of future oil demand could come from petrochemicals.[16,17] In the context of decreasing fossil fuel production to achieve net zero emissions, these investments could represent future stranded assets.[18] Alternately, commitment to using these investments may perpetuate the production of fossil carbon plastics. Globally the average petrochemical plant is 10-15 years old and most plants will likely operate for 30 years and beyond.[19] As a result, installation of new petrochemical infrastructure could significantly delay the transition to non-fossil fuel plastic feedstocks or create what is termed a Carbon Lock-In.[20]

3.2 Cost Competitiveness as a Key Barrier to Bio-Derived Plastics

Bio-based plastics still represent less than 1% of the >400 million tonnes of plastic produced annually.[2] In part, this arises from the higher relative costs of bio-based plastics compared to fossil-carbon plastics. Bio-based polymers can cost 3-4 times more than established fossil plastics.[21] Fossil-carbon plastics derive from petrochemicals, and are co-products of oil and gas extraction for fuels. Petrochemicals are currently relatively cheap and readily available—at least for as long as the global energy supply is reliant on fossil fuels. Further, the oil industry is mature, with refinery processes having been established for many decades, resulting in almost 200 years of knowledge and research. This, along with economies of scale, contributes to the cost-effectiveness of the refining process. Other factors driving higher bio-based plastic costs include fossil subsidies and higher bio-feedstock costs. For those bio-derived plastics that are already price-competitive, e.g. PLA, Starch blends and cellulose, costs and availability of adequate composting and/or recycling processes continue to challenge large scale production.

3.3 Digital Platforms for Trading Recycled Plastics

Digital trading platforms are an emerging tool to coordinate the information and exchange of recycled plastics. Like many digital platforms for increasing material circularity and market efficiency, these platforms are emerging in both formal and informal recycling economies. In the US and Europe companies such as Circular (US), Cirplus (Germany), and Circularise (Netherlands) provide digital platforms to enable efficient and quality-controlled exchange of recycled plastics. Large corporations with commitments for increased recycled content in their packaging are the prime users. These platforms may help to close the gap in demand and availability of recycled plastics. Different models of platforms such as plasticbank® help to work within the informal collection and recycling activities by providing income for the labour and plastic collected and connecting the plastic to global consumers. [22] This approach brings a more explicit social and development component to the recycled plastic economy. A case study on non-biodegradable solid waste, including plastic, in Indonesia demonstrated the potential for digitalisation in improving resource recovery and increasing employment. [23]

4.0 Supplementary Information of Legal Concepts in Section 3

The text that follows supplements Section 3 in the paper with further detail on key concepts, and additional illustrations of legal actions.

4.1 Circular Economy

There is no one agreed definition of the circular economy. In a glossary of terms prepared by the secretariat ahead of the first round of negotiations of the new international agreement on plastics (INC-1), the circular economy is described, by reference to an earlier UNEA Resolution, [24] as being:

"One of the current sustainable economic models, in which products and materials are designed in such a way that they can be reused, remanufactured, recycled or recovered and thus maintained in the economy for as long as possible, along with the resources of which they are made, and the generation of waste, especially hazardous waste, is avoided or minimized, and greenhouse gas emissions are prevented or reduced, can contribute significantly to sustainable consumption and production." [25]

A recent legal definition can be found in the EU Taxonomy Regulation, in which circular economy is defined as:

"an economic system whereby the value of products, materials and other resources in the economy is maintained for as long as possible, enhancing their efficient use in production and consumption, thereby reducing the environmental impact of their use, minimizing waste and the release of hazardous substances at all stages of their life cycle, including through the application of the waste hierarchy." [26]

To compare, the following definition is found in the US Save Our Seas 2.0 Act:

"The term 'circular economy'' means an economy that uses a systems-focused approach and involves industrial processes and economic activities that— (A) are restorative or regenerative by design; (B) enable resources used in such processes and activities to maintain their highest values for as long as possible; and (C) aim for the elimination of waste through the superior design of materials, products, and systems (including business models)." [27]

Both definitions reflect key elements of the understanding developed through the Ellen McArthur foundation, namely that the circular economy is:

“A systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution. It is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature.” [28]

4.2 Environmentally Sound Management (ESM) of Wastes

ESM is a concept that has its origins in the non-binding 1987 Cairo Guidelines and Principles for the ESM of Hazardous Wastes, [29] but has been given specific meaning since then through the Basel Convention on the Trade in Hazardous Wastes, a binding treaty with 191 Parties including the EU. [30] The Basel Convention defines ESM as “taking all practicable steps to ensure that [controlled wastes] are managed in a manner which will protect human health and the environment against the adverse effects which may result from such wastes” (Art. 2(8)). The principle of ESM is also supported by regional agreements, such as the Bamako Convention on the Ban of the Import into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes within Africa (1991), which defines ESM in the same manner as the Basel Convention. ESM is both expressed through and incentivised by other mechanisms, also part of the Basel Convention, such as waste minimisation, self-sufficiency, minimising and controlling transboundary movement, etc.

Technical guidelines for the Identification and ESM of Plastic Wastes and for their Disposal were adopted at the sixth Conference of the Parties to the Basel Convention (COP6) in 2002. [31] These Guidelines have recently been updated at COP16 (May 2023) [32] a process which was launched at COP14 in 2019, [33] when the Basel Convention was also amended to bring more plastic wastes within its regulatory scope. [34]

4.3 Recycling

Whether chemical recycling processes falls within the legal definition of recycling or not, is not always clear, and may vary. At the international level, the Basel Convention defines recycling as ‘recycling/reclamation of organic substances not used as solvents’. [35] Energy recovery is listed as a separate process. [36] To compare, EU law makes use of the same definitions of energy recovery and recycling, whereby pyrolysis and gasification are explicitly included in the latter and not the former definition, provided the components are used as chemicals rather than subsequently incinerated. [37]

4.4 Sustainable Production and Consumption (SPC/SCP)

Sustainable production and consumption (SPC) has developed into an essential requirement for sustainable development. It is enshrined in Principle 8 of the 1992 Rio Declaration on Environment and Development, as follows:

“To achieve sustainable development and a higher quality of life for all people, States should reduce and eliminate unsustainable patterns of production and consumption and promote appropriate demographic policies.” [38]

Moreover, SPC is one of the Sustainable Development Goals (SDG) formulated at the United Nations Sustainable Development Summit on 25 September 2015. [39] SDG12 is framed as follows: “Ensure sustainable consumption and production patterns”. It is to be achieved through a list of targets, the most relevant for plastics include the following:

> 12.2 By 2030, achieve the sustainable management and efficient use of natural resources

> 12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment

> 12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse

> 12.6 Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle

> 12.7 Promote public procurement practices that are sustainable, in accordance with national policies and priorities

> 12.A Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production

> 12.C Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities

While the principle of SCP is defined differently across different policy instruments, nonetheless it is often defined as “the use of services and related products, which respond to basic needs and bring a better quality of life, while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product, so as not to jeopardize the needs of further generations.” [40]

4.5 Waste Hierarchy

The waste hierarchy is a 'generalized priority order for waste management options and technical approaches' that has found widespread acceptance.[41] In the EU, for instance, it is a cornerstone of the EU Waste Framework Directive (Art. 4).[42] At the global level, it has moreover been incorporated in technical guidance developed in the context of the Basel Convention on the trade in hazardous wastes, adopted by consensus at conference of the parties meetings, which denotes a high degree of general acceptance of the principle across jurisdictions.[43,44] According to the waste hierarchy, waste management options are ranked in the following order of priority: prevention, minimization, reuse, recycling, other recovery including energy recovery, and final disposal. When applying the waste hierarchy, options that deliver 'best overall environmental outcome' are usually encouraged.[43]

4.6 Examples of National Measures that Stimulate Smart Design for a System Change

Across the world, many states have adopted national laws and policies in relation to the plastics sector. A useful database has been compiled by Duke University, at the time of writing (June 2023) updated to January 2023, which is described as "comprehensive at the international level, includes a representative but not exhaustive list of policies at the national level, and an illustrative list of policies at the subnational level".[45] The inventory currently includes close to 900 policies.

A search for the keyword "plastic" in the WTO's Environmental Database shows that since 2009, WTO Members have only notified 241 measures in relation to plastics and the environment that affect trade[46] Over half (143) of the notified measures relating to plastic concern technical barriers to trade (e.g. Belize's certification scheme for biodegradable products,[47] and Bahrain's ban single-use plastic bags[48]); 12 are sanitary and phytosanitary measures (e.g. Korea's revised standards for using recycled resins in food utensils, containers and packages[49]); 29 are quantitative restrictions to trade (e.g. various import bans on plastic bags), 5 public procurement measures (all notified by Japan to ensure a minimum ratio of recycled plastics and to change plastic bottled water into bottled water[50]); 41 import licencing measures (e.g. Australia's system of approvals for certain industrial chemicals[51]); 9 are subsidies and countervailing measures (e.g. Australia's waste levies and exemptions to encourage recycling,[52] and Thailand's financial encouragement for the transformation of plastic waste into fuel oil[53]); and 2 are trade facilitation measures.[54] Note that not all of these notifications in fact regulate the plastics sector, such as a notification by Oman regarding copyright laws that also include plastic art (IP/N/1/OMN/C/2 of 27 January 2011).[54]

Another source of information is the surveying work carried out by the ad hoc open-ended expert group (AHEG) on marine litter and microplastics, which was established through United Nations Environment Assembly (UNEA) Resolution 3/7. In 2020, the AHEG was tasked to "[t]ake stock of existing activities and action by governments, regional and global instruments, international organizations, the private sector, non-governmental organizations and other relevant contributors to reduce marine plastic litter and microplastics with the aim of the long-term elimination of discharge into the oceans". The methodology of the exercise and the data received is accessible online.[55] The report notes that "[a]ctions tended to target the clean-up and consumption end of the plastic lifecycle with fewer actions reported to prevent plastics discharging to the ocean or that ‘turn off the tap’ by addressing design of products or raw material design”.

Section 3 in the paper highlighted some of these national measures as examples of how national laws and policies can both directly and indirectly target smart design for a system change.

4.7 Structural Issues

Section 3 of the paper highlights the need for legal coherency between different areas of law to better enable operators to make sustainable design decisions, in particular among laws on chemicals, wastes, and products. For example, legal clarity is needed over when waste ceases to be waste (when it has undergone a recovery operation) and on waste quality standards for plastics, as has been discussed in the EU context. [56]

Far-reaching national measures (like imposing or prohibiting particular types of materials or products) also risk becoming barriers to trade and would not conform with World Trade Organisation (WTO) law. [57,58] Indeed, national plastics-related measures have already led to Specific Trade Concerns (STCs) being raised at the WTO’s Committee on Technical Barriers to Trade (TBT Committee), [59] a forum for WTO members to consult over matters related to the Agreement on Technical Barriers to Trade (TBT Agreement). [58] A dispute before the WTO is less likely where domestic measures are adopted by direct implementation of a multilateral agreement, [60] and any *prima facie* breach may be more easily justified where the policy objectives of the measure are shared by the international community. [61] There is, therefore, a strong argument in favour of a coherent international approach. Moreover, domestic measures that mandate product characteristics or their related process and production methods (technical regulations) [62] benefit from the presumption of WTO conformity when they are based on international standards, [63] which they are required to do where effective and appropriate international standards exist. [64] This also provides an argument in favour of an international set of plastics design standards, such as through the International Organisation for Standardization (ISO). Note that a “standard” in this context (and unlike how the term is used more broadly in this paper, in particular for the purpose of Figure 4) is defined as a “document approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for products or related processes and production methods, with which compliance is not mandatory. It may also include or deal exclusively with terminology, symbols, packaging, marking or labelling requirements as they apply to a product, process or production method.” [65] International design standards moreover provide a basis for voluntary domestic design standards, thereby serving to harmonize response options. [66]

5.0 Supporting Materials for Scenario Roadmaps

The transition roadmap visualises how some of the interventions set out in Section 3 of the manuscript could transform the current ‘business as usual (BAU)’ scenario into a sustainable circular plastics economy by 2050 (transition to the bold system change scenario, or BSC). As described in the paper, four targets are important to achieve the bold system change:

1. **Reduce plastic demand.** Eliminate and substitute 50% of all plastic materials and products.
2. **Switch to renewable plastics.** Replace all fossil fuel-based plastics with those sourced from alternative feedstocks, accelerating carbon recirculation through use of biomass and CO_2.
3. **Maximize recycling.** Design plastic materials and products for circularity, and ensure that 95% of plastics are recycled.
4. **Minimize environmental impacts.** Remove all sources of hazards to organisms and pollution to the environment, as well as decrease the carbon foot-print throughout the plastics lifecycle.

It is critical to note that the roadmap presents one of a set of possibilities to achieve these targets by 2050. As such, as is the case for Section 3, the interventions listed are not intended to be exhaustive, instead serving as an example list of actions to help drive the global plastic economy towards the circular transition.

5.1 Methodology

5.1.1 Sources

Sources used in the creation of the roadmap were primarily taken from independent academic or government reports.

5.1.2 Scenarios

The roadmap presents two 2020-2050 scenarios:

1. **Business-As-Usual (BAU).** This scenario follows the expected growth in demand for plastics by 2050 with no specific demand reduction interventions being taken.
2. **Bold-System Change (BSC**). This scenario depicts an initial rise in demand from 2020, before demand declines and trends toward the targets set by the bold-system change scenario in 2050.

To estimate the impacts of these scenarios, we focus on the following outputs:

1. Total volume of plastics (Mt).
2. Carbon equivalent emissions (Mt-CO_2 equivalents).
3. Carbon capture uptake (Mt-CO_2).

These roadmaps constitute a visual summary of the evolution of projected demand and the fate of plastic materials and their correlated CO_2 equivalents emissions. Their main purpose is to highlight the stark differences in CO_2 equiv. emissions between the BAU pathway and an economy that progressively implements the selected interventions. We additionally include the efforts needed to scale up carbon capture, as this allows the BSC scenario to also reach net-zero emissions by 2050. Taken together these scenarios emphasize the need for speed in making the interventions and the resulting cuts in carbon emissions.

To visualize this analysis the BSC scenario groups the data in the following manner:

Table S17: Description of Interventions for BSC Roadmap

Data Type	Groups	Description
Plastic Types	**Petrochemical Plastics**	These polymers, which represent >99% of all polymers consumed today, are derived directly form the refining of crude oil. They encompass HDPE, LDPE, PP, PS, PVC, PUR, PET, and others, as defined in the SI preface.
	Renewable Plastics	These polymers are exemplified in this roadmap by bio-PE, bio-PET, PLA, starch blends, and PHA (see SI preface). However, these polymers are unlikely to represent the entire future market share in 2050, particularly since they currently represent less than 1% of all plastics. We use them to illustrate the potential for the transition to a circular plastics economy; however, in future meeting all properties and performances will need further material development and new renewable polymers.
Plastic Lifecycle Stages	**Production**	These include all the industrial processes occurring upstream (before use), e.g. production of polymers and conversions to final products.
	End-of-Life	These encompass all the processes occurring after plastic materials meet the end of their lifespan and include landfilling, incineration, recycling (physical, chemical, and biological), and biodegradation (industrial composting and anaerobic digestion).

Table S18: Impact of Interventions for the BSC Roadmap

Term	Definition
Early adopter economies	Describes economies likely to adopt various initiatives linked to renewable plastics first. The set of these economies is likely to vary from initiative to initiative as needs, interests, and capacities to respond are different.
Global adoption	Describes the expansion of renewable plastics to a global scale, and includes economies not captured in the early adopter category. This set of economies will vary from initiative to initiative in a similar manner to the early adopter category.
Carbon Capture and Utilization (CCU)	CCU entails capturing CO_2 for reuse. It can be used directly or indirectly through chemical transformation into a range of products.

5.1.3 Interventions

To construct the transition roadmap, interventions are applied to the BAU scenario to reduce its emissions impact and plastic volumes. The process to analyse the impact of each intervention is as follows.

First, each intervention is described in detail (building on those discussed in Section 3). These descriptions outline the main features of an intervention and identify the plastic types and lifecycle stages it could plausibly impact. This list is designed to target the largest opportunities for circularity, including decarbonising energy sources for plastic processes, reducing demand for plastics, increasing recycling, and ensuring enough feedstocks are available to scale up renewable plastics, among others. [8] Each intervention is given a timeframe over which it could take place to help achieve the 2050 targets, ensuring that any preconditions for particular interventions can be met by actions taken previously. Interventions overlap temporally, thus resulting in a 'layering' or 'building up' effect over time.

Second, the target and type of each intervention are identified. The set of targets correspond to the four interventions identified in the paper (reduce plastics demand, switch to renewable plastics, maximise recycling, and minimize environmental impacts). The type refers to the mechanisms an intervention deploys in order to be effective, including:

- Permissions and prohibitions;
- Standards;
- Financial mechanisms;
- Market-based;
- Infrastructure building.

Third, the impact of each intervention is described to determine its possible impacts on plastic types and stages of the plastic lifecycle. The sizing process draws on the available academic literature for each intervention. Due to uncertainties associated with the potential impact of each intervention, the sizing is undertaken qualitatively. Sizing takes into account the entire impact of the intervention from concept to scale-up up to deployment by 2050.

Finally, after sizing and classifying the interventions, the net effect of the intervention impacts was translated to the net zero roadmap curves.

5.1.4 Plastic Types and Lifecycle Outputs for BSC Scenario - Functional Forms

This sub-section describes the functional forms and methodology underpinning the shape of the circularity roadmap graphs.

5.1.5 Initial increase in emissions and volume

The initial rise in plastic emissions reflects the time taken for any interventions to reduce plastic demand to take effect, the time to phase in renewable plastics, and the minimum time for new infrastructure to start to be built. Thus, in the immediate future, demand for plastics (and thus plastics emissions) will continue to grow. Some interventions can reduce demand in the short term and cause early reductions compared to the BAU scenario (such as bans on ‘harmful’ and ‘unnecessary’ plastics), but significant reductions will only occur when renewable alternatives become widely available and cost-competitive with petrochemical plastics.

The initial rise in demand is reflected in the functional form of certain lifecycle stages, including virgin production, conversion, incineration, landfilling and recycling. This rise in demand was estimated using an exponential growth function where the rate of growth slows over time. The compound annual growth rate (CAGR) of demand for plastics as a whole is estimated at ~5%.[67] This CAGR was assumed to decline approximately linearly over time from 5% in 2020 to 0% in 2035, with emissions and volumes reaching a peak in approximately 2035.

5.1.6 Decline in Emissions and Volumes to Reach Bold System Change Targets

Once emissions and volumes have reached their peak, they begin to decline to meet the bold system change targets by 2050. It is worth noting that this estimated decline includes the recycling lifecycle stage because, even as the total share of plastics recycled continues to grow over time, the emissions attributed to recycling over time will decline after reaching an initial peak under the BSC scenario.

The decline after the initial peak was modelled using a sigmoid function. The sigmoid function was selected because it accounts for the possibility that some phase-outs will be straightforward, while others will be hard to address.

The sigmoid function used was:

$$S(x) = \frac{A}{1 + e^{-k(x - x_0)}} + B$$

A = Amplitude

k = Gradient

x_o = Midpoint

B = Y-axis displacement of the curve

The midpoint of the sigmoid curve describing the decline in emissions after an initial rise was set at 2040, which accounts for a very ambitious timescale for such major system change and allows for reasonable fits to the sigmoid function. The amplitude and y-displacement were estimated by the decline required to meet the targets of the bold system change scenario in 2050 determined in this article. The gradient of the curve was adjusted to meet the 2050 value.

5.1.7 Growth of Renewable Plastics and Circularity Waste Processing Mechanisms Over Time

Not all lifecycle stages experience an early peak in emissions before declining. Some, such as industrial composting and anaerobic digestion grow throughout the entire BSC scenario. Carbon capture and utilization also follow a continual growth pattern during the BSC roadmap, and are treated using the same functional form.

The continual growth of some interventions (and carbon capture and utilization) was also modelled using a sigmoid function. The sigmoid function was selected due to its ‘tails’ of slow rates of change at the beginning and end of the curve. This mirrors the characteristic that some plastics are comparatively easy to phase out/in while some are extremely challenging, meaning that there is likely to be a similar ‘tailing’ effect in implementation. Furthermore, sigmoid curves show that the bulk of transition tends to happen within a relatively short period of time. This rapid acceleration of change is proposed to apply to the transition from petrochemical to renewable plastics as cumulative investments, innovation and technology breakthroughs rapidly increase the rate of system change over time until diminishing rates of change take over at the ‘tail end’ of challenging substitutions and phase-outs.

The sigmoid function used was:

$$S(x) = \frac{A}{1+e^{-k(x-x_0)}} + B$$

A = Amplitude

k = Gradient

x_o = Midpoint

B = Y-axis displacement of the curve

The amplitude and y-displacement were determined by the 2050 end values for each lifecycle stage and plastic type. The mid-point and gradient were adjusted so that these 2050 values can be met, starting from the initial 2020 values.

5.1.8 Timing and sequencing of interventions

The sequence of interventions and their suggested dates were developed based on leading policy literature (see table S22). Just as with the interventions themselves, these dates should be treated as indicative, presenting only the general time frame in which an intervention could occur in order to meet the transition scenario outlined in the BSC roadmap.

For every piece of literature, the dates and sequencing of a particular intervention were noted and compared to dates and sequences associated with similar interventions in other leading sources. Comparing the timelines of these sources to the 2050 time horizon of this article allowed interventions to be sequenced in a similar order and with similar timings to leading literature, with some adjustment for differences in 'end dates' of sources. As a result, the report reflects whether an intervention tends to be classified as occurring early, in the middle, or late in literature, and identifies a 'consensus date' that most sources could feasibly come to when examining a similar intervention on the time scale and in the context of this report. This assessment process is described in further detail in Table S22.

5.2 Roadmap Outputs

From 2020 to approximately 2025, the emissions of the BAU and BSC scenarios are approximately equivalent. From 2025 onwards, BSC emissions begin to significantly diverge from BAU as early interventions to reduce demand (for example, reductions in anticipation of ‘unneccessary’ plastics and ‘harmful’ plastics bans in 2028). Peak emissions from the plastic system are reached in 2035 under the BSC scenario.

Significant reductions in emissions across the BSC pathway are driven by the use of clean energy in the plastic lifecycle after 2035, and the removal of subsidies and investments in oil and gas systems from 2040 onwards (which significantly enhance the cost-competitiveness of renewable plastics).

The move to circular plastic systems requires sizable investment in the waste collection and processing capabilities worldwide. Without interventions designed to enhance these systems, significant levels of environmental plastic pollution are likely to remain alongside large ‘opportunity gaps’ to utilise plastic waste as feedstocks. Given the challenges in operationalising waste collection and processing systems, the BSC roadmap aims to introduce significant volumes of renewable biodegradable and compostable plastics during the time that 'collection gaps' are filled.

By 2050, the circular economy for plastics proposed under the BSC scenario still generates some emissions. Thus the system requires carbon removal to reach net zero. The volume of removals is illustrated by the blue line, and a brief explanation of interventions helpful to support carbon capture, removal, and utilization is found in Table S21.

Through the BSC scenario including carbon removals, approximately 49-55% of carbon equivalent emissions are saved compared to the BAU scenario from 2020 to 2050.

5.3 Tables of Interventions

Table S19: List of interventions, and descriptions to foster a BSC scenario for a circular plastics system.

Note this list is not intended to be exhaustive but illustrative of the sorts of interventions and timelines that may be required to reach circularity.

Inter-vention #	Type of Approach	Contribution to Target	Policy Aim	Description
1	Financial support for R&D of renewable plastics	Switch to renewable plastics	Financial mechanism	Subsidies to encourage R&D related to renewable plastics can have significant effects in shifting demand in the long term, as they increase the cost-competitiveness of these materials compared to petrochemical plastics. This intervention suggests deploying subsidies or tax credits for R&D related to developing renewable plastics and enhancing the sustainability of production and recycling processes. Current examples of financial mechanisms to support R&D in plastics include the Research and Development Tax Credit in the UK, the European Innovation Council (EIC) Accelerator and the Horizon Europe SME Instrument, and the Special Fund for Guiding Technology Innovation in China. [68-70] International cooperation will enhance the effectiveness of these financial mechanisms, which could be coordinated through a mechanism like a global plastics treaty. This intervention is important because a suite of fit-for-purpose, efficient, and recyclable materials must be deployed at scale to reach circularity.
2	Foster sustainable biomass production	Switch to renewable plastics	Market-led	The scale-up of renewable plastics requires sufficient volumes of sustainable biomass that do not damage livelihoods, human welfare, and ecological systems. Reaching these volumes of biomass requires careful resolution of competing uses of land (e.g., food production, reforestation, and biomass production) through consultative, welfare-oriented, spatially aware, and ecologically centred approaches. [21] Sustainable biomass production is critical because it is required to supply carbon inputs to a circular economy for plastics. However, implementation of this intervention ought to be sensitive to a variety of local contexts, with roll-outs staggered and adapted to local economic contexts.

3	Tax unnecessary plastics	Reduce plastics demand Minimize environmental impacts	Financial mechanism	This intervention proposes imposing a tax on ‘unnecessary’ plastics to complement the roll-out of bans. The tax can be used to shift demand to renewable plastic alternatives and foster the scale-up of renewable plastics ahead of an outright ban. [71] This measure proposes to extend small charges on items such as plastic bags has become common in countries such as the UK, New Zealand, Ireland, and Norway, expanding the scheme further onto other common single-use items and ‘unnecessary’ plastics in general (e.g., types of packaging). [72-75] A similar measure has been suggested by the OECD. [76] This intervention is likely to decrease the share of waste entering end-of-life streams, while also reducing virgin production and conversion. [77] The effectiveness of this intervention depends on eliminating the demand for ‘unnecessary’ plastics, finding suitable substitutes, and properly disposing of substitutes (requiring appropriate collection and waste management infrastructure). [77,78]
4	Producer voluntary commitments	Reduce plastics demand Switch to renewable plastics Maximise recycling Minimize environmental impacts	Market-led	Producer voluntary commitments to reducing plastic demand and increasing recyclability can have notable impacts on demand. [79] Current examples of voluntary commitments include Coca Cola (goal of making all of its packaging 100% recyclable by 2025), Unilever (50% reduction in plastic and 100% of packaging recyclable or reusable by 2025), and H&M (100% recycled or sustainably sourced materials in its clothing by 2030). [80-82] While these commitments are not legally binding, they signal a broad commitment of market leaders to address circularity of plastics. This intervention suggests a continuation of producer voluntary commitments at the current rate with significant pledges from a large share of market players over coming decades, assuming these commitments are carried out and targets are met. This intervention will increase the share of renewable plastics to petrochemical plastics, while fostering recycling, composting, and digestion disposal methods.
5	National and regional deposit return systems	Maximise recycling	Financial mechanism	Deposit return systems offer a refund for each plastic item recycled by a consumer and have had a significant positive effect on increasing recycling rates (and decreasing incineration and landfilling) in nations and regions where implemented.

		Minimize environmental impacts		This intervention proposes scaling up deposit return schemes in early adopter economies early in the BSC roadmap, with the rest of the world to follow (where these initiatives may provide additional incentive for consumers to participate in waste collection infrastructure). [83] Examples of existing deposit return schemes include Germany (98%+ consumer recycling rate), Norway (95%+), and Sweden (90%+).[83-85] There is an infrastructure barrier to these schemes however, as regions and states require appropriate waste management and recycling facilities for deposit return systems to function properly. [72] Investment in appropriate infrastructure is therefore a precondition for this intervention.
6	Ban 'unnecessary' plastics	Reduce plastics demand Minimize environmental impacts	Restrictions and prohibitions	This intervention proposes the banning of 'unnecessary' plastics such as certain single-use items (straws, cups, bags), and hard-to-recycle/reuse items, such as certain packaging. Bans on 'unnecessary' plastic items are likely to increase demand for substitute volumes of recyclable alternatives (both petrochemical and renewable) and decrease incineration and landfilling as a significant volume of items entering these waste streams is eliminated. [86] The effectiveness of this intervention depends on reducing the demand for 'unnecessary' plastics, finding suitable substitutes, and properly disposing of substitutes (requiring appropriate collection and waste management infrastructure). [87] Examples of current bans of unnecessary plastics include the EU in 2019 (plates, cutlery, straws, stirrers, and cotton bud sticks) and Taiwan. [88,89] While more jurisdictions are likely to adopt these measures in the future (e.g., bans are currently under consideration in Canada and India), bans will have to have (near) global coverage to have a significant impact. Bans could be implemented individually, or through global harmonization (e.g., a global plastics treaty). [90]
7	Ban 'harmful' plastics	Minimize environmental impacts Reduce plastics demand	Restrictions and prohibitions	A ban on 'harmful' plastics would encompass for example oxo-degradable plastics and sources of microplastics, among other plastics with 'harmful' additives or decomposition properties. Microplastics are a particularly important category, [91] as in 2016, 11% of plastic leakage into the environment was due to microplastics. [9] Major sources of microplastics include tyre dust, pellets, cigarette filters, clothing and textiles, cosmetics, and hygiene products. [9] A ban is likely to cause a small reduction in demand, with an affiliated small decline in virgin production and conversion. This intervention is particularly effective if bans on 'harmful' plastics are effective at reducing plastic demand overall, rather than shifting demand to substitutes. This intervention builds on extant bans in a variety of jurisdictions. For example, bans on oxo-degradable are in force in the EU (2019), [88] and under consideration across various jurisdictions. [92] The UNEP has called for a global ban on microplastics by 2040, which is likely to be achieved. [71,90] This intervention is of significant importance because of its co-benefits for water quality, environmental and ecosystem health, and human, and non-human welfare. [93] A global plastics treaty could be an effective vehicle for

				enabling and coordinating these bans. [90]
8	Construct recycling infrastructure for new renewable plastics in early adopter economies	Maximise recycling Minimize environmental impacts	Infrastructure	The phase-in of renewable plastics at scale requires the upgrading of recycling infrastructure (particularly of chemical recycling) across many economies. This is because renewable plastics require different waste processing equipment and processes. As a result, even economies that have very high collection and waste processing rates of plastics currently in circulation will require infrastructure upgrades to adapt to renewable plastics. [94] This intervention outlines the phase-in of new recycling infrastructure for renewable plastics. This will affect waste management related lifecycle stages. Proceeds of a tax on ‘unnecessary’ plastics or EPR regulation could contribute to the financing of new infrastructure.
9	Financial support for scaling renewable plastics production	Switch to renewable plastics	Financial mechanism	The total investment need in the plastics system to facilitate a sustainable transition is estimated at 1.18 billion USD, most of which needs to be allocated to subsidies to ensure cost competitiveness and scale-up of renewable plastics. [9,21] This intervention suggests deploying subsidies and tax credits as a bridging measure to account for increased costs of renewable plastics as technologies are scaled. Caution in designing financial mechanisms is necessary to ensure they genuinely benefit green and circular plastics and are not invested into ‘harmful’ or ‘unnecessary’ plastic production. [9] This intervention is important because renewable plastics need to be available at scale and cost-competitive in a circular plastic system.
10	EPR schemes in early adopter economies	Reduce plastics demand Switch to renewable plastics Maximise recycling	Financial mechanism	EPR programs in early adopter economies amount to a financial mechanism where producers pay to use existing infrastructure. By requiring producers to reduce ‘unnecessary’ and ‘harmful’ plastics and account for elements of waste disposal, reuse, and recycling, the burden on the overall system can be reduced, enabling savings to be reinvested into infrastructure upgrades. [95,96] Thus, EPR schemes in early adopter economies are expected to increase renewable plastic shares, and increase recycling, composting and anaerobic digestion, while reducing virgin production, associated conversion, landfilling, and incineration. This intervention suggests strengthening and expanding mandatory EPR legislation across early adopter economies. By the end of 2024, for example, EU member states must ensure that EPR schemes are established for all packaging.

11	Eco-design Regulations	Reduce plastics demand Minimize environmental impacts Switch to renewable plastics	Standards	Eco-design regulations aim to make products more environmentally sustainable, and in so doing, may reduce the use of plastics and enhance durability, reusability, and recyclability. Relevant measures include standards for component design for separability, so that items made of different materials can be easily disaggregated during waste processing, and standards that set a percentage recycled plastics for use in production of new goods. [97,98] Reusability rules are also included, which can take a variety of forms including models such as 'refill at home', 'refill on the go' (e.g., in a store), 'return on the go' (e.g., at collection points in supermarkets), and 'return from home' (e.g., collection services).[15] Phasing in reusability of packaging is expected to offer a 10 billion USD business opportunity, while significantly reducing the volumes of single-use plastics in circulation. [79] Examples of eco-design regulations includes the EU Ecodesign Directive, [99] which contributes to sustainable development by increasing energy efficiency and the level of protection of the environment, though note its current limited application to energy-using and energy-related products. A broader EU Ecodesign Regulation has now been proposed (2022) that would apply to a broad range of products and set a wide range of targeted product requirements based on the sustainability and circularity, such as product durability, reusability, upgradability and reparability, the presence of substances of concern in products, product energy and resource efficiency, recycled content of products, product remanufacturing and high-quality recycling, and for reducing products' carbon and environmental footprint. Standards on how to design packaging (packaging requirements) may lead to some of the same outcomes, such as the EU requirement for 55% of plastic packaging to be reusable or recyclable by 2030 under Article 6.1 of the Packaging Directive. [100] The design and implementation of packaging and recyclability regulations needs to be sensitive to local economies as there are varying capabilities to collect and recycle plastics in different jurisdictions. Thus, regulations will be differentiated across economies. [101] Eco-design and related regulations are likely to cause a small decline in virgin production and conversion, and an increase in recycling plastics streams. [101] This intervention suggests for eco-design regulations to be meaningfully in force across early adopter economies in early stages of the transition, with other economies to follow.
12	Collaborative global approach to plastics	Reduce plastics demand Switch to renewable plastics	Standards Restrictions and prohibitions	Greater collaboration between nation States and non-State actors is both a policy aim in and of itself, and a means to achieve other ends (e.g., global bans and prohibitions, innovation collaboration). A collaborative global approach to plastics can be envisaged in different ways, for example through cooperation under existing international instruments like the Basel Convention on the Trade in Hazardous Wastes, or by adopting the new global plastics treaty (negotiations for which are currently ongoing under UN auspices). [102] The Basel Convention was recently amended to include almost all plastic wastes within its regulatory scope, and new technical guidelines on the environmentally sound management of plastic wastes have now been adopted. In line with the Convention's key provisions, this should result in a greater reduction of plastic wastes, and have upstream effects

		Maximise recycling Minimize environmental impacts	Financial mechanism	on product design for recyclability, in line with the waste hierarchy. Moreover, the Basel Convention has established a number of regional centres to provide technical assistance, capacity building, and to promote the transfer of technology to developing country Parties and economies in transition. Plastic wastes were included as a priority waste stream for its 2022-2025 technical assistance plan, under which over 50 Parties already currently receive technical assistance to strengthen their capacity for the environmentally sound management, the control and transboundary movements of, and prevention and minimization of plastic wastes. [103] These regional centres moreover cooperate in the international negotiations of the new plastics treaty which, if adopted, would provide a political statement of intent to address plastics, and presumably recognize that developing economies require significant support to do so. In line with UNEA Resolution 5/14, this intervention assumes that a global approach to plastics will include provisions that: promote sustainable production and consumption of plastics through, among other things, product design and environmentally sound waste management, including through resource efficiency and circular economy approaches; promote national and international cooperative measures to reduce plastic pollution in the marine environment, including existing plastic pollution; specify arrangements for capacity-building and technical assistance, technology transfer on mutually agreed terms, and financial assistance; promote research into and development of sustainable, affordable, innovative and cost-efficient approaches; and address compliance. [102] Global collaboration on plastics also involves setting standard definitions. Clearly defined recyclability and clear waste processing requirements are expected to benefit recyclables and renewable plastics. [104,105]
13	Recycling targets	Maximise recycling	Standards	Setting recycling targets reduces the demand for non-recyclables. Current examples of recycling targets include the EU Packaging and Packaging Waste Directive (recycling 55% of plastic packaging by 2025 and 70% by 2030, requirement for all plastic packaging to be reusable or recyclable by 2030), and China's municipal waste plan (target of recycling 35% of municipal waste by 2020 and 45% by 2030). [82,100,106] This intervention calls on early adopter economies to set recycling targets in the early stages of the BSC roadmap, with varying levels of ambition depending on feasible scale-up of waste processing and recycling infrastructure. Recycling targets must be supported by adequate waste collection and recycling infrastructure and enable businesses and consumers to have access to appropriate substitutes for petrochemical plastics when plastic use is challenging to phase out. [9] The global establishment of recycling targets will take longer, given issues with infrastructure scale-up. Targets should take into account what plastics can be collected and recycled with the infrastructure in place, meaning that targets will vary between economies.
14	Green public procurement	Switch to renewable	Financial mechanism	This intervention suggests implementing green public procurement criteria in early adopter economies in the early to mid-stage of the BSC roadmap, calling for recyclable and renewable plastic products. The ramp up of GPP worldwide

		plastics		should follow prior to 2050. This should have significant impacts on increasing use of recyclables and renewable plastics due to the purchasing and market signal setting influence of governments. [21,107]
15	Halt global expansion of fossil fuel infrastructure	Switch to renewable plastics	Infrastructure	The expansion of fossil fuel infrastructure through projects such as Keystone XL and upgraded LNG terminals in Europe help make petrochemical plastics cost-competitive in the long term. [8,21,108] Current investment is considerable: For example, the IEA cites examples of Saudi Aramco and ADNOC, which planned to increase infrastructure spending by about 15-30% in 2022. [108] This intervention proposes to halt the expansion of petrochemical infrastructure globally beyond current levels as soon as possible. This would cause a significant decline across all petrochemical plastics and foster uptake of renewable plastic alternatives.
16	Use clean energy in plastic processing	Switch to renewable plastics	Infrastructure	Deploying clean energy in plastic production has a significant impact on emissions reduction, both for petrochemical and renewable plastics. It significantly reduces the emissions of energy-intensive lifecycle steps such as conversion, recycling, anaerobic digestion, and composting. Zheng et al estimate that energy is the largest lever to decarbonise plastics. [8] This intervention suggests decarbonising energy globally as soon as possible, with burdens for carbon removal undertaken by wealthy economies to compensate for residual fossil emissions in developing economies.
17	Waste collection and disposal infrastructure available globally	Maximise recycling Minimize environmental impacts	Infrastructure	Waste collection and disposal infrastructure must be scaled up significantly on a global level as soon as possible in order to meet the rates of recycling required by the circularity scenario in this paper. ‘Breaking the Plastic Wave’ analysis by Pew Trust found that 500,000 people need to be connected every day until 2040 to close the ‘collection gap’ and reduce current rates of over 40% of global plastics leaking into the environment at its end of life. [9] Interventions to ramp up waste collection include implementing a regular collection service that visits households, rolling out the use of rubbish storage such as bags or bins, and establishing local depots for households to deposit waste (especially if there is a complementary deposit return system in place). [109] Systems will need a differentiated approach for urban and rural environments, where collection at scale is extremely challenging. [9,109] Constructing waste collection infrastructure would increase the volume and emissions of waste disposal steps as more plastics enter the end-of-life phases, but decrease net environmental impact as plastic leakage is prevented. [110] Interventions to scale up waste collection infrastructure in developing economies should account for the large informal sector linked to waste management in many countries. Approximately 15% of all waste is collected for recycling by the informal sector, compared to 12% by the formal sector (with the remainder going to disposal or leaking into the environment). [9] Currently waste collection is often organised independently by local companies, and

				not provided by government services. Efforts to scale up infrastructure should aim for a 'just transition' that ensures employment and know-how of the informal economy is incorporated. [9,109] Appropriate disposal mechanisms must be deployed in parallel to collection infrastructure. [9] Disposal in the long-term focusses on recycling, composting, and digestion, but may also initially include incineration (optimally with energy recovery and carbon capture) and landfilling to prevent leakage into the environment. Infrastructure should be designed to accommodate emerging types of plastics that are likely to contribute large volumes in the future. For circularity, the transboundary movement of plastic waste should be minimized and only take place if environmental sound management can be ensured abroad, in line with the Basel Convention. Again, initiatives should consider a just transition for local informal sectors affiliated with waste disposal. The design of disposal infrastructure should also bear in mind urban and rural differences: in rural settings it may be appropriate to focus on composting and digestion rather than recycling, and to adjust the mix of plastics used toward biodegradable and compostable materials. Scaling up waste infrastructure is a significant challenge that requires extensive funding. It's estimated that waste collection accounts for 19% of budgets of local authorities in low income countries, and 11% in lower middle and upper middle-income countries. [9] Funding burdens could be assisted through support under the Basel Convention, financial mechanisms in the plastics treaty, other climate commitments, or reinvestment of plastic tax revenues (perhaps sourced worldwide).
18	Compostable and biodegradable plastics available at scale	Minimize environmental impacts	Restrictions and prohibitions Financial mechanism	Given challenges of collection infrastructure in developing economies, this intervention suggests scaling up the share of renewable compostable and biodegradable plastics. These plastics can break down relatively quickly, meaning that the net effect of plastic leakage into the environment is less severe. However, these plastics can still cause environmental harm (for example via ingestion by animals). The shift could be enabled through either regulations, or subsidies. This intervention recognises the challenges of the 'collection gap' and aims to provide a reasonable 'backstop' in cases where collection is challenging or unlikely to scale quickly. [9] Assuming demand is substituted from other materials to compostable and biodegradable, the lifecycle emissions and volumes will not be significantly affected. This intervention is of significant importance because it is essential to reducing 'harmful' plastics in geographies with less developed collection and disposal infrastructure.
19	Remove global fossil fuel subsidies	Switch to renewable plastics	Financial mechanism	Fossil fuel subsidies play a significant role in reducing the raw material and energy costs of petrochemical plastics. [21] Oil and gas subsidies, therefore, pose a significant headwind for phasing out petrochemical plastic products. [8] The International Monetary Fund (IMF) estimates that global fossil fuel subsidies total US$5.9 trillion per year. [111]

				This intervention suggests removing all fossil fuel subsidies as soon as possible so that renewable plastics become more cost-competitive. This would cause a significant decline across all petrochemical plastics and foster the uptake of renewable plastic alternatives.
20	EPR schemes established globally	Reduce plastics demand Switch to renewable plastics Maximise recycling Minimize environmental impacts	Financial mechanism	EPR schemes at a global scale should be treated differently to those in early adopter economies due to differences in waste collection and processing infrastructure. EPR schemes currently do not exist in significant capacities in many developing economies. This intervention suggests that specially designed schemes should be introduced toward the mid-to later stages of the BSC roadmap. These schemes could involve companies importing plastics into developing economies to pay a tax to fund the expansion and maintenance of collection and waste processing infrastructure. [112] They could also include requirements to import a higher share of compostable and biodegradable plastics to reduce the impact of plastics leakage into the environment.

Table S20: Estimated sizing of interventions, and their impact on plastic types and lifecycle stages.

Intervention		Plastic Type (Volume)		Lifecycle Stage (Emissions)						
Inter-vention #	Type of Approach	Petrochemical Plastics	Renewable Plastics	Virgin Production	Conversion	Landfilling	Incineration	Recycling	Industrial Composting	Anaerobic Digestion
1	Financial support of R&D of renewable plastics	Minor decrease	Moderate increase	No effect	No effect	No effect	No effect	No effect	No effect	No effect
2	Foster sustainable biomass production	No effect	Moderate increase	No effect	No effect	No effect	No effect	No effect	No effect	No effect
3	Tax 'unnecessary' plastics	No effect	No effect	Minor decrease	Minor decrease	Moderate decrease	Moderate decrease	Minor decrease	Minor decrease	Minor decrease
4	Producer voluntary commitments	Moderate decrease	Significant increase	Moderate decrease	Moderate decrease	Moderate decrease	Moderate decrease	Moderate increase	Moderate increase	Moderate increase
5	National and regional deposit return systems	No effect	No effect	Minor decrease	Minor decrease	Significant decrease	Moderate decrease	Moderate increase	No effect	No effect
6	Ban 'unnecessary' plastics	No effect	No effect	Minor decrease	Minor decrease	Moderate decrease	Moderate decrease	Minor decrease	Minor decrease	Minor decrease
7	Ban 'harmful' plastics	No effect	No effect	Minor decrease	Minor decrease	No effect	No effect	No effect	No effect	No effect
8	Construct recycling infrastructure for new renewable plastics in early adopter economies	No effect	No effect	No effect	No effect	Significant increase	Significant increase	Significant increase	Significant increase	Significant increase
9	Financial support for scaling renewable plastics production	Minor decrease	Moderate increase	No effect	No effect	No effect	No effect	No effect	No effect	No effect
10	EPR schemes in developed economies	Minor decrease	Minor increase	Moderate decrease	Moderate decrease	Moderate decrease	Moderate decrease	Moderate increase	Moderate increase	Moderate increase

Inter-vention #	Type of Approach	Petrochemical Plastics	Renewable Plastics	Virgin Production	Conversion	Landfilling	Incineration	Recycling	Industrial Composting	Anaerobic Digestion
11	Eco-design Regulations	Minor decrease	Minor increase	Minor decrease	Minor decrease	No effect	No effect	Minor increase	No effect	No effect
12	Collaborative global approach to plastics	Moderate decrease	Moderate increase	Minor decrease	Minor decrease	Minor decrease	Minor decrease	Minor increase	Minor increase	Minor increase
13	Recycling targets	No effect	No effect	Minor decrease	Minor decrease	Significant decrease	Moderate decrease	Moderate increase	No effect	No effect
14	Green public procurement	Moderate decrease	Moderate increase	Moderate decrease	Moderate decrease	Moderate decrease	Moderate decrease	Moderate increase	Moderate increase	Moderate increase
15	Halt global expansion of fossil fuel infrastructure	Significant decrease	Significant increase	No effect	No effect	No effect	No effect	No effect	No effect	No effect
16	Use clean energy in plastics processing	No effect	No effect	Significant decrease	Significant decrease	No effect	No effect	Significant decrease	Significant decrease	Significant decrease
17	Waste collection infrastructure available globally	No effect	No effect	No effect	No effect	Significant increase	Significant increase	Significant increase	Significant increase	Significant increase
18	Compostable and biodegradable renewable plastics available at scale	No effect	Moderate increase	No effect	No effect	No effect	No effect	No effect	No effect	No effect
19	Remove global fossil fuel subsidies	Significant decrease	Significant increase	No effect	No effect	No effect	No effect	No effect	No effect	No effect
20	EPR schemes established globally	Minor decrease	Minor increase	Moderate decrease	Moderate decrease	Moderate decrease	Moderate decrease	Moderate increase	Moderate increase	Moderate increase

Table S21: Carbon Capture and Utilisation Interventions

Intervention		
Inter-vention #	**Type of Approach**	**Description**
A	R&D for ‘novel’ CCU methods	This intervention proposes significant investment into further developing 'novel' carbon capture and utilization methods including BECCS, DACS, biochar, enhanced rock weathering, and ocean alkalinization. [113-115] ‘Novel’ methods are required under almost all climate management plans to limit warming to 1.5 degrees globally, with a sequestration target of 450-1,100 $GtCO_2$ by 2100. [113] This intervention suggests that significant R&D efforts should be in place world-wide by 2025.
B	R&D for land-based CCU methods	This intervention proposes significant investment into refining 'land-based' carbon removal and utilization methods, including best practices for afforestation and reforestation, peatland and wetland restoration, and soil carbon sequestration. [113,114,116] Land-based carbon removal and utilization approaches have significant benefits due to both their sequestration potential, and co-benefits for biodiversity and ecological system health. This intervention suggests that significant R&D efforts should be in place world-wide by 2025.
C	‘Novel’ CCU plan	The deployment of 'novel' carbon removal and utilization methods requires careful planning to ensure sufficient infrastructure, land zoning, and resource management conditions are in place. It’s best practice to create ‘clusters’, where carbon capture facilities are closely connected to industries requiring carbon inputs. [113,115] Plans will require coordination of significant stakeholder groups, including government, business, communities, academic groups, and national institutes. This intervention suggests that a detailed plan should be developed by 2028 in parallel to R&D efforts.
D	Land-use plan	The deployment of land-based carbon removal and utilization methods requires careful management of competing demands for land, such as food production or residential areas. [116] A clear plan must be developed to allocate appropriate space for land-based removals and utilization, in consultation with stakeholders and affected communities. Trade-offs will be required, and must be carefully assessed and socialised with the welfare of affected communities in mind. This intervention suggests that a detailed plan should be developed by 2028 in parallel to R&D efforts.
E	Scale-up of 'novel' CCU	To effectively scale up 'novel' carbon removal and utilization methods, viable business models, stable policy, and public buy-in must be created. [115] This may entail government support such as subsidised infrastructure, direct subsidies to companies, tax credits, or other financial incentives. Scale-up also requires addressing societal and political concerns of the wider community with ongoing public engagement. [113] This intervention suggests that scaling processes should be well-underway by 2033.
F	Scale-up of 'land-based' CCU	To effectively scale up 'land-based' carbon removal and utilization methods, viable business models, stable policy, and public buy-in must be created. [116] This may entail government support such as subsidised infrastructure, direct subsidies to companies, tax credits, or other financial incentives such as compensation to landowners transforming their land into forests. Scale-up also requires addressing societal and political concerns with ongoing public engagement. This intervention suggests that scaling processes should be well-underway by 2030.

Table S22: Table Assessing Sequencing and Timing of Interventions

Inter-vention #	Type of Approach	Sequencing logic	Timing logic	Suggested Start Date
1	Financial support for R&D of renewable plastics	• A wide grouping of policy reports across governments, international organisations, and academia identify financial support for the development of renewable plastics as an important early intervention to help accelerate the development of sustainable plastic alternatives[9,117,118]	• As adequate financial support a key enabler for the plastic system transition[9,117] and can be offered unilaterally by particular countries or businesses, we follow Wang and Pretorius to suggest this intervention occur at scale by 2025 (early in the transition roadmap), which broadly aligns with the argument of the Nordic Council of Ministers for 'early' implementation. • 2025 is a conservative date compared to 'Breaking the Plastic Wave', which recommends significant funding scale-up for the plastic transition by 2022. Due to challenges in designing and rolling out funding schemes at scale, we account for a slight delay compared to 'Breaking the Plastic Wave'	2025
2	Foster sustainable biomass production	• Fostering renewable biomass production renewable plastics as an important early intervention to help accelerate the development of sustainable plastic alternatives. The OECD notes the challenges of sourcing sufficient sustainable biomass (both socially and ecologically), [76] a challenge which we recognise. Through significant reduction in plastic demand and increased recycling, the roadmap aims to minimise raw material inputs into the plastic system. • 'Breaking the Plastic Wave' also identifies the importance of finding alternative feedstocks early on in the plastic transition. [9]	• As sourcing sustainable biomass inputs is a key enabler for a sustainable plastic system[117] and significant action can be undertaken unilaterally by particular countries or businesses, we suggest this intervention occur at scale by 2025 in parallel to demand reduction schemes, and investments in recycling infrastructure across the next 25 years. • 2025 aligns with OECD and 'Breaking the Plastic Wave' suggested timelines	2025
3	Tax unnecessary	• Wang and Pretorius as well as the Nordic	• As reducing demand is essential for a sustainable	2025

	plastics	Council of Ministers identify taxes as helpful early intervention to fund other aspects of the plastics transition, such as subsidies for green plastics and R&D. [117,118] • A wide grouping of policy reports across governments, international organisations, and academia highlight the effectiveness of introducing a tax early in the plastic transition, due to its significant impact on reducing plastic volumes. [9,76,118]	plastic transition[117] and action can be taken unilaterally by particular countries or businesses, we suggest this intervention to occur at scale by 2025 in order to reduce material inputs required and minimise stress on plastic collection and waste infrastructure in coming decades. • The OECD's Global Plastics outlook suggests implementation of plastic taxes as early as 2021, and 'Breaking the Plastic Wave' suggests all demand reduction measures should be in place by 2022, [9] making 2025 a conservative start date for plastic tax deployment at scale • Deployment of such taxation mechanisms over time will be differentiated, beginning sooner in early-adopter economies than in later adopters. [9,76,118]	
4	Producer voluntary commitments	• Wang and Pretorius discuss the benefit of sequencing producer voluntary commitments early on in the plastics transition as they help prepare the plastics industry for a transition to bio-based feedstocks. They suggest to include these commitments in a global plastics treaty. [117] • 'Breaking the Plastic Wave' and the Nordic Council of Ministers highlight the importance of undertaking measures to reduce demand immediately, including producer oriented interventions such as voluntary commitments. [9,118]	• Wang and Praetorius illustrate the effectiveness of coordinating producer voluntary commitments at a global scale through a treaty mechanism. [117] Given that treaty negotiations aim to conclude in 2024, [117] we selected 2025 as a start date for this intervention on the roadmap • 2025 is a conservative start date compared to 'Breaking the Plastic Wave', which argues for a 2022 start-date for significant producer commitments. [9]	2025
5	National and regional deposit return systems	• The OECD's global plastics outlook highlights that policy interventions will be needed in the next 10 years to ensure increased uptake of recycling by 2050. [76] • 'Breaking the Plastic Wave' and the Nordic Council of Ministers showcase the importance of consumer behaviour and recycling-oriented intervention early, as it is relatively easy to implement and ensures sufficient supply of recycled feedstocks. [9,118] However, both highlight the importance of	• As an increase in recycling is key enabler for the transition and deposit return schemes can be offered unilaterally by particular countries or businesses, we suggest this intervention to occur at scale by 2025 in early adopter economies order to meet sustainable plastics by 2050. Early timing where suitable infrastructure is present is important to minimise virgin feedstock requirements for plastic by increasing recycled material inputs. [9] • 2025 is a conservative date compared to 'Breaking the Plastic Wave' which argues for implementation	2025

		having sufficient collection and waste infrastructure in place, and recommend a staggered roll-out of deposit return systems depending on a country's level of infrastructure development.	of similar schemes by 2022.[9] • The Nordic Council of Ministers argues that interventions aimed at increasing recycling require sufficient infrastructure in order to be effective.[118] As a result, a date of 2025 targets early adopter economies where collection and recycling infrastructure tends to be mature,[9] with later adopter economies to follow over subsequent decades.	
6	Ban 'unnecessary' plastics	• A wide grouping of policy reports across governments, international organisations, and academia argue for early bans of 'unnecessary' plastics early on in the plastics transition as a way of reducing production volumes.[9,76,118] Some suggest to include these bans in a global plastics treaty.[117]	• Wang and Praetorius illustrate the effectiveness of coordinating bans at a global scale through a treaty mechanism.[117] Given that treaty negotiations aim to conclude in 2024,[117] we select 2025 as a start date for this intervention in early adopter economies. In economies were bans lead to significant impacts to health and welfare due to a lack of alternatives, or where significant regulatory coordination is required, bans will phase in over the coming decades. • 2025 is a conservative date compared to 'Breaking the Plastic Wave' which argues for implementation of bans for certain plastics by 2022.[9] Given the challenge of rolling out, coordinating, and enforcing bans, we selected 2025 as the roadmap date for early adopters, with others to follow until 2050.	2025
7	Ban 'harmful' plastics	• A wide grouping of policy reports across governments, international organisations, and academia argue for early bans of harmful plastics early on in the plastic transition (such as oxo-degradable plastic) as a way of quickly reducing pollution and environmental damage.[9,76,118] Some suggest to include these bans in a global plastics treaty.[117]	• Wang and Praetorius illustrate the effectiveness of coordinating bans at a global scale through a treaty mechanism.[117] Given that treaty negotiations aim to conclude in 2024,[117], we select 2025 as a start date for this intervention on the roadmap. • This is a conservative date compared to 'Breaking the Plastic Wave' which argues for implementation of bans by 2022.[9]	2025
8	Construct recycling infrastructure for new renewable	• The OECD's Global Plastic Forecast highlights the issue of insufficient infrastructure as a major contributing factor to low recycling levels. To move toward circularity, the OECD recommends	• In alignment with the OECD's Global Plastic Forecast, we select 2030 as a date by which significant recycling infrastructure upgrades must be made in early adopter economies.[76] • This date aligns with 'Breaking the Plastic Wave'	2030

	plastics in early adopter economies	significant policy and investment action for infrastructure from today to 2050 (and beyond).[76] • Infrastructure development is identified as a critical but challenging transformation enabler by 'Breaking the Plastic Wave', which advocates for development as early as possible.[9]	report, which argues that early intervention is needed in order to significantly improve infrastructure provisions by 2030.[9]	
9	Financial support for scaling renewable plastics production	• 'Breaking the Plastic Wave' highlights the need for early and proactive funding of a sustainable transition for plastic, including the design of new business models and products.[9] Sufficient funding is required for all subsequent interventions, making this intervention particularly critical in the early stage of the roadmap.	• 'Breaking the Plastic Wave' argues for scaling-up of sources of funding for sustainable plastic by 2022.[9] However, sourcing significant funding required is likely to be challenging on a global scale, meaning the roadmap selects 2030 as the date by which significant financial support will be in place globally. The selected date is a balance between the urgency of early funding, the requirement to meet circularity by 2050, and the challenges of scaling up appropriate financial mechanisms. 2030 broadly aligns with the dates of the OECD's largest interventions coming into effect, such as significant uptake of recycling and sustainable feedstocks, incentives to reduce plastic demand and replace petrochemical feedstocks with sustainable alternatives. We suggest that by 2030, in this climate, the financial case for supporting and scaling sustainable plastics will be more favourable than in 'Breaking the Plastic Wave' 2022 scenario, while still coming early enough to meet 2050 circularity goals.	2030
10	EPR schemes in early adopter economies	• Wang and Praetorius and the Nordic Council of Ministers argue that EPR proof-of-concept schemes should be as soon as possible in a coordinated manner internationally.[117,118] • 'Breaking the Plastic Wave' argues for early implementation of schemes to change consumer and producer behaviour,[9] but recognise the need for geographically differentiated roll-out depending on the economic context of different economies.	• Wang and Praetorius illustrate the effectiveness of coordinating EPR schemes at a global scale through a treaty mechanism.[117] Given that treaty negotiations aim to conclude in 2024 and industry would likely require several years to design and implement EPR schemes,[117] we select 2030 as the start date for this intervention on the roadmap. • This is a conservative date compared to 'Breaking the Plastic Wave' which argues for implementation similar schemes by 2022.[9]	2030

11	Eco-design Regulations	• The OECD's global plastics outlook projects that mismanaged waste volumes will remain at relatively high levels in non-OECD countries (23% of total plastic waste volume in 2060).[76] The OECD estimates that eco-design interventions can help address these volumes over the coming decades by making recyclable components easier to process, extending lifespans, and increasing repairability.[76] • 'Breaking the Plastic Wave' suggests for mechanisms like eco-design regulations in the middle stages of the transition, once sufficient waste collection and processing infrastructure is in place to benefit from eco-design at scale.[9]	• Due to the challenge of establishing eco-design regulations both locally and globally through a vehicle like a global plastics treaty,[117] we selected 2030 as a start date for eco-design regulations to have notable impacts on reducing mismanaged waste volumes. This is broadly in line with OECD's Global Plastics Outlook, which recommends a significant scale of eco-design regulations by 2040 with the aim of a plastic system transition by 2060 (as opposed to 2050 in this paper).[76]	2030
12	Collaborative global approach to plastics	• Wang and Praetorius discuss the importance of a global plastics treaty to create a collaborative global approach as soon as possible.[117] In discussing various important facets that could be included in such a treaty, they highlight the complexity of various issues and recognise that resultant interventions may take several years to enter full effect. Thus, though a treaty is an important coordination element, it may enter into force in the mid-range of the bold system change transformation.	• Due to the complexity of global collaboration on plastics, for example through a treaty, we suggest providing significant time for firstly negotiation, and secondly for negotiated initiatives to enter into force at scale. As a result, we suggest 2030 as a reasonable date to see a plastics treaty have notable effects on the global plastic system.	2030
13	Recycling targets	• A wide grouping of policy reports across governments, international organisations, and academia argue that policy interventions will be needed to ensure increased uptake of recycling by 2050.[9,76,118] • Recycling targets are a key part of the OECD's recommendations, with faster timelines for developed economies compared to developing economies. The OECD recommends targets ramping up	• As an increase in recycling is key enabler for the transition and deposit return schemes can be offered unilaterally by particular countries or businesses, we suggest this intervention to occur at scale by 2030 in early adopter economies (with others to follow) order to meet sustainable plastics by 2050. • This timeline for recycling targets at scale by 2030 is faster than the OECD's forecast which aims for widespread targets by 2040 (differentiated by early adopter and other economies), however in order to	2030

		from 2030 to 2060.[76] • Both the OECD and 'Breaking the Plastic Wave' highlight the importance of having sufficient collection and waste infrastructure in place, and recommend a staggered roll-out of targets depending on a country's level of infrastructure development.[9,76]	create a sustainable plastic system by 2050 targets serve as a useful market signal and structure for governments to plan infrastructure, financial mechanisms, and procurement plans. • This is a conservative date compared to 'Breaking the Plastic Wave' which argues for immediate implementation.[9] However, the roadmap recognises the importance of first sufficiently scaling infrastructure so that increased recycling volumes can be appropriately processed (e.g., to be prepared as recycled feedstocks)	
14	Green public procurement	• 'Breaking the Plastic Wave' and the Nordic Council of Ministers showcase the importance of shifting consumer behaviour in the short- and mid-term through systematic interventions to change behaviour.[9,118] This also includes shifts in large public sector actors via pathways like Green Public Procurement.	• Green public procurement is a powerful market signal for sustainable plastic, but requires a sufficiently mature industry to meet public sector demand. As a result, it has been given a date of 2030 in the roadmap. • This aligns with 'Breaking the Plastic Wave' policies, which recommends the world-wide implementation of such schemes by 2030.[9]	2030
15	Halt global expansion of fossil fuel infrastructure	• The OECD points out the relationship between the widespread availability of fossil fuel sources and the continuing reliance on petrochemical plastic.[76] • Halting the expansion of fossil fuel infrastructure (and eventually phasing it out) is an important component of reducing global reliance on petrochemical feedstocks.[8,76] • 'Breaking the Plastic Wave' recommend halting infrastructure expansion as soon as possible, with significant effects by 2022.[9] • The IEA also recommends an early phase-out date of petrochemical infrastructure, but recognises significant associated challenges.[119]	• In recognition of the significant political-economic challenges affiliated with ending fossil fuel infrastructure expansion, the roadmap selects a date of 2035. This extended deadline offers additional time for renewable energy to become cost-competitive in more regions and economic sectors, improving the economic case for decommissioning and slowing expansion of fossil fuel infrastructure.[119]	2035
16	Use clean energy in plastic	• Zheng and Suh show the significant share of carbon emissions of the plastic sector	• The OECD recommends a phase-out path of fossil fuel energy from 2020-2050. Our roadmap target of	2035

	processing	attributable to fossil fuel energy and argues for a transition to renewables as soon as possible (recognising that this entails significant challenges).[8] • Due to the high share of emissions attributable to energy, efforts to switch to clean energy should occur early in the plastic transition. However, significant infrastructure requirements mean such a transition will likely require until the mid-2030s to scale renewable energy alternatives globally.[119]	2035 falls within a reasonable date on the transition pathway, as renewable energy is expected to have significantly scaled by the mid-2030s in the OECD scenarios.[76] • The selected 2035 date aligns with IEA scenarios of the required energy systems transition to meet net zero energy emissions in 2050, as sufficient clean energy for industrial processes such as plastics production is estimated to be available by the mid-2030s.[119]	
17	Waste collection and disposal infrastructure available globally	• The OECD's Global Plastic Forecast and 'Breaking the Plastic Wave' Report highlight the issue of insufficient infrastructure as a major contributing factor to plastics leakage into the environment. To minimise environmental impacts and move toward circularity, both recommend significant policy and investment action for infrastructure from today to 2050 (and beyond).[9,76] • The Nordic Council of Ministers and 'Breaking the Plastic Wave' highlight the importance of a just transition for the informal sector.[9,118] • The challenges entailed in expanding infrastructure worldwide means that scholarly consensus agrees that, though urgent, infrastructure availability will occur toward the end of a bold system change transformation.[9,76,118] •	• In broad alignment with the OECD's Global Plastic Forecast, we select 2045 as a date by which significant recycling infrastructure upgrades must be made across all economies.[76] • This is a conservative date compared to 'Breaking the Plastic Wave' which argues for global infrastructure scale-up by 2030.[2] However, given the challenge of infrastructure expansion, we selected 2045 as a more feasible year • 2045 remains an ambitious timeline for global availability of waste collection and disposal infrastructure, with significant investment into the infrastructure gap required from 2023 onwards	2045
18	Compostable and biodegradable plastics available at scale	• The OECD's global plastics outlook projects that mismanaged waste volumes will remain at relatively high levels in non-OECD countries (23% of total plastic waste volume in 2060).[76] Introducing compostable and biodegradable plastics helps reduce the environmental impact of	• Due to the challenge in scaling up production of biodegradable and compostable plastic and co-ordinating its deployment in economies with limited recycling infrastructure, we propose this intervention to take effect by 2035. This provides a stop-gap measure to reduce waste leakage until collection and waste processing infrastructure is sufficiently	2035

		mismanaged waste streams, and also alleviates some pressure on recycling infrastructure (which is likely to require significant development and expansion in developing economies). • 'Breaking the Plastic Wave' highlights the important of materials innovation on areas such as composability and biodegradability in the mid-2020s. [9]	developed • 2035 is a conservative date compared to 'Breaking the Plastic Wave', which recommends earlier implementation by 2025. However, given the challenge of developing, scaling, and cost-competitiveness of compostable and bio-degradable plastics by 2025, 2035 was selected as a more realistic date (coinciding with proposed reductions in renewable energy cost, and additional measures to shift demand away from petrochemical plastics)	
19	Remove global fossil fuel subsidies	• The OECD points out that subsidies and other mechanisms that lower fossil fuel prices compared to sustainable alternatives prolong the reliance of plastic on petrochemical feedstocks and fossil fuel energy in the plastic system. [76] • Removing subsidies will reduce the competitiveness of petrochemicals and fossil energy, providing a strong cost-based incentive to examine alternatives • The OECD, IEA, and 'Breaking the Plastic Wave' advocate for systemic measures to reduce fossil competitiveness as soon as possible. [9,76,119] However, all organisations recognise challenges associated with subsidies and accept that, though urgent, it is likely to occur later in a bold system change transformation.	• The IEA estimates that by the mid-2030s, the cost of renewable energy will substantively reduce while its share in the energy mix grows. [119] As a result, this report suggests a conservative date of 2040 for the end of fossil fuel subsidies. This allows the renewable energy industry to mature and scale globally to provide a feasible alternative to fossil fuels, and accounts for time to organise and enforce the removal of subsidies.	2040
20	EPR schemes established globally	• Wang and Praetorius and the Nordic Council of Ministers argue that EPR proof-of-concept schemes should be as soon as possible in a coordinated manner internationally. [117,118] • 'Breaking the Plastic Wave' argues for early implementation of schemes to change consumer and producer behaviour, [9] but recognise the need for geographically differentiated roll-out depending on the economic context of different economies.	• Wang and Praetorius illustrate the effectiveness of coordinating EPR schemes at a global scale through a treaty mechanism. [117] Given that treaty negotiations aim to conclude in 2024 and industry would likely require several years to design and implement EPR schemes, [117] we select 2035 as the start date for global EPR systems on the roadmap. • This allows 5 years for EPR to become established in early adopter economies, before scaling to a global level.	2035

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