Supplementary Information

to the article "The material flow analysis model REMIND-MFA: Global demand scenarios and circular flows for plastics, steel, and cement"

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S1 Detailed general methods with equations

This section describes the general methods applied to all materials in more detail. The stock extrapolation (Subsection S1.1) and the trade extrapolation (Subsection S1.2) extend the corresponding methods sections of the main paper (Sections 2.4 and 2.5), while the trade adjustments (Subsection S1.3) are additional information not covered in the main paper.

S1.1 Stock extrapolation

In-use stock per capita for each region and end-use category is regressed on the logarithm of GDP per capita using a logistic function.

To fix conventions, let $L(p, x)$ be the logistic curve over x parametrized by $p = (\alpha, \beta, \gamma)$, that is

$$L(p, x) = \alpha/(1 + \exp(-4\,\gamma\,(x - \beta))), \tag{S1}$$

where α is the saturation level, β is the horizontal offset and γ is the growth rate. Their effects on the function are shown in Figure S1.



Figure S1: Parameter variations of the logistic function, which is used for regression of per-capita in-use stocks over the logarithm of GDP per capita.

We define the normalized logistic function $\tilde{L}(\varphi, x) = L(p, x)/\alpha$:

$$\tilde{L}(\varphi, x) = 1/(1 + \exp(-4\,\gamma\,(x - \beta))), \tag{S2}$$

with reduced parameters $\varphi = (\beta,\, \gamma)$.

In the following, t denotes the time variable (year), r indexes the region, and u indexes the in-use category.

We multiply the prescribed saturation level α_{tot} for each material with lifetime-weighted prescribed limit end-use inflow shares σ_u to obtain the saturation level α_u for each in-use category u, i.e., $\alpha_u = \alpha_{\text{tot}}\,\sigma_u$. The per-capita historical stocks $h_{r,u}(t)$ for each region and good (as calculated from the historical MFA) are normalized by this end-use-specific saturation level α_u to obtain the normalized historical stocks $\tilde{h}_{r,u}(t) = h_{r,u}(t)/\alpha_u$.

S1.1.1 Step 1: Common regression

We first calculate the common regression for normalized per-capita in-use stocks $f_u^{(1)}(t)$ (where the superscript (1) indicates Step 1 of the stock extrapolation procedure) using

$$f_u^{(1)}(t) = \tilde{L}\big(\hat{\varphi}_u^{(1)},\, x_r(t)\big), \tag{S3}$$

where $x_r(t)$ is the standardized base-10 logarithm of the GDP per capita[1] of that region and

$$\hat{\varphi}_u^{(1)} = \arg\min_{\varphi} \left(\sum_{t,r} \big(w_r(t)\,(\tilde{L}(\varphi, x_r(t)) - \tilde{h}_{r,u}(t))\big)^2 \right) \tag{S4}$$

are the reduced parameters minimizing the L^2-distance from the historical stocks, with GDP shares $w_r(t)$ as region weights.

S1.1.2 Step 2: Regional adaptation

In this step, we vary the parameter set from Step 1 by region. This step aims to balance continuation of historical in-use-stock development trends with limited deviation from the common regression in Step 1.

[1] Strictly speaking, the GDP per capita is divided by 1 USD/cap to make it unitless before taking the logarithm.

To this end, we define the regional curve

$$f_{r,u}^{(2)}(t) = L\big(\hat{p}_{r,u}^{(2)},\, x_r(t)\big) \tag{S5}$$

with the region-specific parameter set $\hat{p}_{r,u}^{(2)}$. Note that we allow deviating saturation levels $\hat{\alpha}_{r,u}^{(2)} \neq 1$, so we now use the full logistic function L with parameter vector p. We obtain $\hat{p}_{r,u}^{(2)}$ from the minimization

$$\hat{p}_{r,u}^{(2)} = \arg\min_{p} \Big(W_{T_a}\, T_a(p) + W_{T_r}\, T_r(p) + W_{T_d}\, T_d(p) + W_{D_\alpha}\, D_\alpha(p) + W_{D_\beta}\, D_\beta(p) + W_{D_\gamma}\, D_\gamma(p) \Big) \tag{S6}$$

where T_a, T_r, T_d, D_α, D_β, and D_γ are penalty functions, and W_i the corresponding weights.

The terms

$$\begin{aligned} T_a(p) &= \big(L(p, x_r(t_0)) - \tilde{h}_{r,u}(t_0)\big)^2, \\ T_r(p) &= \left(\frac{L(p, x_r(t_0)) - \tilde{h}_{r,u}(t_0)}{\tilde{h}_{r,u}(t_0)} \right)^2, \qquad \text{and} \\ T_d(p) &= \Big(\frac{d}{dt}\Big|_{t=t_0} \big(L(p, x_r(t))\big) - \frac{d}{dt}\Big|_{t=t_0} \big(\tilde{h}_{r,u}(t)\big) \Big)^2 \end{aligned} \tag{S7}$$

all penalize deviations of the regionally adapted function from the normalized historical in-use stocks $\tilde{h}_{r,u}$ at the last historical time step t_0. In particular, the terms T_a and T_r penalize absolute and relative deviations of the function value, whereas T_d penalizes deviations of the derivative w.r.t. time[2].

On the other hand, the terms

$$\begin{aligned} D_\alpha(p) &= (\alpha - 1)^2, \\ D_\beta(p) &= (\beta - \hat{\beta}_u^{(1)})^2, \quad \text{and} \\ D_\gamma(p) &= (\gamma - \hat{\gamma}_u^{(1)})^2 \end{aligned} \tag{S8}$$

penalize deviations of the parameters α, β, and γ from the parameters of the common regression $\hat{\varphi}_u^{(1)} = \big(\hat{\beta}_u^{(1)}, \hat{\gamma}_u^{(1)}\big)$.

The weights of these parameter terms are chosen empirically to achieve a good trade-off and are the same for all materials. Their values are

$$W_{T_a} = 20, \quad W_{T_r} = 1, \quad W_{T_d} = 4000\,\mathrm{yr}^{-2}, \quad W_{D_\alpha} = 10, \quad W_{D_\beta} = 7.5, \quad \text{and} \quad W_{D_\gamma} = 0.025. \tag{S9}$$

S1.1.3 Step 3: Transition smoothing

Since Step 2 does not guarantee an exact match of value and derivative to historical data, a blending procedure from historical data $\tilde{h}_{r,u}(t)$ to the logistic curve $f_{r,u}^{(2)}(t)$ is performed.

The same procedure is later also applied to in-use stock inflows (Section S1.1.5) and to trade (Section S1.2.7). It is therefore described in a generic notation, applied separately to each region and category: $h(t)$ denotes the historical data up to the last historical year t_0, the target value is labeled $s(t)$ (s as in "set point", another term for target in this context), and the smoothed transition is labeled $y(t)$. One or two dots denote first and second time derivatives $\dot{y}(t) = \frac{dy}{dt}$ and $\ddot{y}(t) = \frac{d^2y}{dt^2}$.

For the stocks, this notation means that $h(t) = \tilde{h}_{r,u}(t)$, $s(t) = f_{r,u}^{(2)}(t)$, and $y(t) = f_{r,u}^{(3)}(t)$.

The blending procedure is carried out in the time domain. The smoothed function $y(t)$ is obtained by solving an initial value problem (a differential equation) with initial conditions $y(t_0) = h(t_0)$ and $\dot{y}(t_0) = v_0$, where the initial slope v_0 is estimated from the recent historical trend. Its second derivative is controlled as described below, and its function value and first derivative are determined by time integration.

The second derivative is determined to drive the smoothed function $y(t)$ towards its target $s(t)$. To this end, a critically damped PD-controller is used, which means that the second derivative has two terms: one is proportional to the difference in the function value (the "P" in "PD", as in "proportional"), whereas the other is proportional to the differences in the derivative (the "D" in "PD", as in "derivative").

The resulting differential equation then reads

$$\ddot{y}(t) = -2k\, (\dot{y}(t) - \dot{s}(t^*)) - k^2\, (y(t) - s(t)). \tag{S10}$$

[2]The derivative is taken with respect to time, not with respect to GDP per capita, to avoid numerical issues in case of stagnating or declining historical GDP per capita.

The constant k is a damping factor which determines the convergence speed. It is set such that in a static problem with $\dot{s}(t) = 0$ and $\dot{y}(t_0) = 0$, the difference $y(t) - s(t)$ is reduced by 95 % within a pre-defined approaching time τ, which is chosen between 30 and 65 years. The asterisk t^* is part of a look-ahead modification described below.

The differential equation is solved with a semi-implicit (symplectic) Euler scheme, that is by starting at $t = t_0$ and executing the following three assignments year by year.

$$\begin{aligned} \ddot{y}(t) &= -2k\,(\dot{y}(t) - \dot{s}(t^*)) - k^2\,(y(t) - s(t)) \\ \dot{y}(t + \Delta t) &= \dot{y}(t) + \ddot{y}(t)\,\Delta t \\ y_p(t + \Delta t) &= y(t) + \dot{y}(t + \Delta t)\,\Delta t \end{aligned} \tag{S11}$$

Here, Δt is the time step width, one year in this case. The value $y_p(t)$ is the preliminary smoothed function. The actual smoothed function $y(t)$ is finally obtained through the nudging procedure

$$y(t + \Delta t) = \theta(t + \Delta t)\,s(t + \Delta t) + (1 - \theta(t + \Delta t))\,y_p(t + \Delta t) \tag{S12}$$

with the nudging factor

$$\theta(t) = 1 - \exp\big(-\rho(t)\,\Delta t\big), \qquad \rho(t) = \frac{\lambda}{\tau}\left(\frac{t - t_0}{\tau}\right)^2. \tag{S13}$$

The nudging rate $\rho(t)$ increases over time to accelerate the complete convergence of the smoothed function to the target function. The coefficient λ is chosen such that the nudging alone would reduce the difference $y(t) - s(t)$ by 95 % within τ. In control theory, an integration term is often added to the PD-controller to achieve complete convergence, making it a PID controller. In the present case, this led to oscillations in the smoothed function, which is why a nudging procedure was used instead.

Since the set point $s(t)$ is known a priori for all years, its future development over time can be used by the algorithm. In particular, the derivative $\dot{s}$ in Eq. (S10) is evaluated at a later time than t, i.e. at $t^* = t + c(t)$, where the look-ahead $c(t)$ decreases linearly from five years to zero within $\tau/2$. This lessens overshoots of the smoothed function if the target function nears saturation.

S1.1.4 Denormalization

Finally, the smoothed normalized per-capita stocks $f^{(3)}_{r,u}(t)$ are multiplied with the good-specific saturation level α_u and with the population of the region r to obtain the in-use stock extrapolation for each region and end-use category.

S1.1.5 In-use stock inflow smoothing

The in-use stock inflow is first computed from the extrapolated stock with a stock-driven dynamic stock model. As this can cause abrupt changes of the inflow at t_0, the transition smoothing of Section S1.1.3 is applied to the inflow, with $h(t)$ the historical inflow, $s(t)$ the inflow from the stock-driven model, and $y(t)$ the smoothed inflow. Negative values of the smoothed inflow are set to zero, and the in-use stock is recomputed from the smoothed inflow with an inflow-driven dynamic stock model. The resulting stock therefore deviates slightly from the extrapolation of Section S1.1.

S1.2 Trade extrapolation

For trade extrapolation, a heuristic was developed that produces plausible future scenarios. As a first step, trade flows of individual regions are extrapolated into the future separately. In a second step, imports and exports are corrected to achieve global market clearing.

In the following, an independent notation is used, such that symbols also occurring in Section S1.1 do not denote the same variables.

S1.2.1 Regional extrapolation

Regionally, a trade market fulfills the mass balance

$$p_r(t) + i_r(t) = e_r(t) + d_r(t), \tag{S14}$$

where p denotes local production, i denotes imports, e denotes exports, and d denotes local demand. Here, t is the year and r is the region.

In the future MFA, the production value chain from material production to end-use is calculated backward, starting with end-use goods demand. This means that first, local demand for end-use products is given, and imports, exports, and local production of end-use products have to be calculated together to fulfill Eq. (S14). Similarly, after calculating local raw material demand from local production of end-use goods, this local demand is known for the raw material trade market as well, and imports, exports, and local production of raw materials have to be calculated together to fulfill Eq. (S14). For scrap or waste markets, on the other hand, supply is known (from the outflow of the in-use stock and collection rates). So for this stage, the local "production" is known, and imports, exports, and local "demand" have to be calculated together.

S1.2.2 Basic scaling

Let us first consider the demand-driven case. Since imports and domestically produced goods are often treated as substitutes, it is a natural choice to keep the import share constant, i.e.

$$\frac{i_r(t)}{d_r(t)} = \frac{i_r(t_0)}{d_r(t_0)}, \tag{S15}$$

where t_0 is the last historical time step. Similarly, the share of locally produced goods that is exported may stay approximately constant, which leads to the scaling

$$\frac{e_r(t)}{p_r(t)} = \frac{e_r(t_0)}{p_r(t_0)}. \tag{S16}$$

S1.2.3 Scaling modification for increasing demand / production

An issue with this implementation is that regions with still very low GDP and therefore low domestic demand and production sometimes have high import and/or export shares, partly due to lacking domestic supply/demand and partly due to lacking data. We thus let the import and export shares of these regions converge toward the global average import/export shares in the last historical year if production or demand have very high relative increases.

This is achieved with the formula

$$i_r(t) = d_r(t) \left(\frac{i_r(t_0)}{d_r(t_0)}\right)^{(1-\alpha)} \left(\frac{\sum_{r'} i_{r'}(t_0)}{\sum_{r'} d_{r'}(t_0)}\right)^{\alpha} \quad \text{for} \quad d_r(t) \geq d_r(t_0) \tag{S17}$$

with a blending factor $0 \leq \alpha \leq 1$, which is a function of relative demand change, i.e., $\alpha(\, d_r(t)/d_r(t_0)\,)$. In particular, we choose α to be the quintic spline

$$\alpha(\delta) = 6\,\delta^5 - 15\,\delta^4 + 10\,\delta^3 \tag{S18}$$

with δ being the logarithm of the relative demand change

$$\delta = \log_{50}(d_r(t)/d_r(t_0)). \tag{S19}$$

Similarly, exports are scaled as

$$e_r(t) = p_r(t) \left(\frac{e_r(t_0)}{p_r(t_0)}\right)^{(1-\alpha)} \left(\frac{\sum_{r'} e_{r'}(t_0)}{\sum_{r'} p_{r'}(t_0)}\right)^{\alpha} \quad \text{for} \quad p_r(t) \geq p_r(t_0), \tag{S20}$$

where α is evaluated with the relative change of production, $p_r(t)/p_r(t_0)$.

S1.2.4 Scaling modification for decreasing demand

For decreasing demand, a different phenomenon occurs: such regions have standing production capacity, which lowers production costs, and often protectionist policies to safeguard these capacities. We therefore assume that exports stay constant in this case, i.e.

$$e_r(t) = e_r(t_0) \quad \text{for} \quad d_r(t) \leq d_r(t_0) \tag{S21}$$

while imports are still scaled proportionally with demand as in Eq. (S15), i.e.

$$i_r(t) = i_r(t_0)\frac{d_r(t)}{d_r(t_0)} \quad \text{for} \quad d_r(t) \leq d_r(t_0). \tag{S22}$$

S1.2.5 Solving for exports and production

Imports only depend on the known variable demand and can therefore be calculated directly. Exports, on the other hand, depend on production (cf. Eq. (S20)), which in turn is determined from the mass balance in Eq. (S14) and thus depends on exports. This equation system is solved in a fixed-point iteration loop. This loop is initialized with constant exports, $e_r(t) = e_r(t_0)$.

In every iteration, Eq. (S14) is solved for $p_r(t)$, after which Eq. (S21) is solved for $e_r(t)$. This updated $e_r(t)$ is then used for the next iteration. Three iterations are used without a convergence criterion, which yields sufficient accuracy.

S1.2.6 Steel scrap trade

Steel scrap trade is calculated analogously to the other trade stages, with the difference that the roles of imports and exports as well as those of demand and production are flipped.

This means that exports are calculated first. They are still scaled with production (here, the domestic scrap supply), as in Eq. (S16), and with the modification of Eq. (S20) for increasing supply. Imports are scaled with demand, as in Eq. (S15), with the modification of Eq. (S17) for increasing demand. Imports and demand are then calculated concurrently with a fixed-point iteration. The modification for decreasing values also applies with flipped roles: exports decline proportionally with decreasing supply, while imports do not decline below their reference value, analogously to Eq. (S21).

S1.2.7 Transition smoothing

The transition smoothing of Section S1.1.3 is applied to the extrapolated imports $i_r(t)$ and exports $e_r(t)$ before global balancing. For each, $h(t)$ is the historical trade flow, $s(t)$ the extrapolated trade flow, and $y(t)$ the smoothed trade flow. Negative values of the smoothed trade flows are set to zero.

S1.2.8 Global balancing

Global market clearing prescribes that global exports equal global imports, i.e.

$$\sum_r e_r(t) = \sum_r i_r(t). \tag{S23}$$

This condition is not necessarily fulfilled after the extrapolation step. Therefore imports and/or exports are multiplied such that their global sums have the same common value $g(t)$ (defined below), i.e.

$$e_r(t) = \tilde{e}_r(t)\frac{g(t)}{\sum_{r'}(\tilde{e}_{r'}(t))}, \qquad i_r(t) = \tilde{i}_r(t)\frac{g(t)}{\sum_{r'}(\tilde{i}_{r'}(t))} \tag{S24}$$

Here, the tilde accent denotes values before the scaling step, and the apostrophe is only added to the summing index r' so as not to be confused with the equation index r.

For future trades, the common value $g(t)$ is determined as the harmonic mean of global imports and exports, i.e.

$$g(t) = \frac{2}{1/\sum_r(\tilde{e}_r(t)) + 1/\sum_r(\tilde{i}_r(t))} \quad \text{for} \quad t > t_0. \tag{S25}$$

The above balancing is also performed for historical trades, as exogenous import and export data from the literature do not always sum to the same global values. In this case, it is assumed that trade volumes are rather under-reported than over-reported, such that the maximum is used for the global common sum instead, i.e.

$$g(t) = \max\left(\sum_r(\tilde{e}_r(t)),\ \sum_r(\tilde{i}_r(t))\right) \quad \text{for} \quad t \le t_0. \tag{S26}$$

S1.3 Trade adjustments

Exogenous trade data are not always consistent with exogenous production and demand data, and extrapolated trade does not account for how much secondary material a region can use. Without correction, this can result in negative flows or unused secondary material. The following mechanisms prevent this.

S1.3.1 Trade capping

In historical years, the net exports of a region are limited to its domestic supply, e.g., net steel exports to domestic steel production. This is applied to the steel and manufactured products trade of steel, the primary and manufactured products trade of plastics, and the cement trade. Gross exports may still exceed supply if they are covered by imports, which represents re-export trade. Net exports are evaluated per good category, since net imports of one category cannot be re-exported as another category. Where the limit is exceeded, exports are reduced accordingly.

Reducing the exports of some regions violates global market clearing. It is restored with the global balancing of Section S1.2.8, where only the opposite trade flows of the unaffected regions are scaled. As this may partially reintroduce the excess, capping and balancing are iterated until convergence.

Analogously, historical net imports are limited to domestic demand for clinker trade (cement) and primary plastics trade. For plastics, the excess net imports of a polymer are first reassigned to other polymers of the same polymer type, as far as their demand allows; only the remainder is removed.

The same procedure is applied to future steel scrap trade: net scrap imports of a region are limited to the amount that its scrap-based steel production can use in addition to domestic scrap. Scrap that is not imported remains in the exporting regions.

S1.3.2 Surplus redistribution

In future years, some regions have more secondary material than they can use domestically, while others could use more. This surplus is redistributed with an auxiliary trade: regions export their surplus and import up to their remaining capacity, and both are scaled to the smaller of the two global sums. This applies to steel scrap exceeding the maximum scrap input to steel production, where the auxiliary trade is added to the extrapolated scrap trade. For plastics, it applies to mechanically recycled polymers and chemically recycled feedstock, each with its own auxiliary trade market.

S1.3.3 Trade-adjusted end-use shares

Historical inflows into the in-use stock are disaggregated into end-use categories with exogenous end-use shares. This is applied to steel (by end use) and plastics (by end use and polymer). The inflow of each category consists of domestic manufacturing and net imports of manufactured goods. If the net imports of one category exceed the inflow given by its end-use share, domestic manufacturing of this category would become negative. In this case, the inflow of the category is set to its net imports instead. The resulting surplus is compensated by reducing the domestic manufacturing of the remaining categories proportionally. Total inflow is thereby conserved, and the end-use shares deviate from the exogenous values only where necessary.

S2 Definition Tables

S2.1 Regions

S2.1.1 REMIND 12-region aggregation

A map of this aggregation is shown in main paper Figure 4, panel a).

Table S1: REMIND 12-region aggregation

Code	Name	Full list of countries
CAZ	Canada, NZ, Australia	Canada, Australia, New Zealand, Heard & McDonald Islands, St. Pierre & Miquelon
CHA	China	China, Hong Kong, Macau, Taiwan
EUR	EU 28	Åland Islands, Austria, Belgium, Bulgaria, Cyprus, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, Faroe Islands, United Kingdom, Guernsey, Gibraltar, Greece, Croatia, Hungary, Isle of Man, Ireland, Italy, Jersey, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden
IND	India	India
JPN	Japan	Japan
LAM	Latin America and the Caribbean	Aruba, Anguilla, Argentina, Antarctica, Antigua & Barbuda, Caribbean Netherlands, Bahamas, St. Barthélemy, Belize, Bermuda, Bolivia, Brazil, Barbados, Bouvet Island, Chile, Colombia, Costa Rica, Cuba, Curaçao, Cayman Islands, Dominica, Dominican Republic, Ecuador, Falkland Islands, Guadeloupe, Grenada, Guatemala, French Guiana, Guyana, Honduras, Haiti, Jamaica, St. Kitts & Nevis, St. Lucia, St. Martin, Mexico, Montserrat, Martinique, Nicaragua, Panama, Peru, Puerto Rico, Paraguay, South Georgia & South Sandwich Islands, El Salvador, Suriname, Sint Maarten, Turks & Caicos Islands, Trinidad & Tobago, Uruguay, St. Vincent & Grenadines, Venezuela, British Virgin Islands, U.S. Virgin Islands
MEA	Middle East, North Africa, Central Asia	United Arab Emirates, Bahrain, Algeria, Egypt, Western Sahara, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Palestinian Territories, Qatar, Saudi Arabia, Sudan, Syria, Tunisia, Yemen
NEU	Non-EU28 Europe	Albania, Andorra, Bosnia & Herzegovina, Switzerland, Greenland, Iceland, Liechtenstein, Monaco, North Macedonia, Montenegro, Norway, Svalbard & Jan Mayen, San Marino, Serbia, Turkey, Vatican City

Continued on next page

Table S1: REMIND 12-region aggregation (continued)

Code	Name	Full list of countries
OAS	Other Asia	Afghanistan, American Samoa, French Southern Territories, Bangladesh, Brunei, Bhutan, Cocos (Keeling) Islands, Cook Islands, Christmas Island, Fiji, Micronesia (Federated States of), Guam, Indonesia, British Indian Ocean Territory, Cambodia, Kiribati, South Korea, Laos, Sri Lanka, Maldives, Marshall Islands, Myanmar (Burma), Mongolia, Northern Mariana Islands, Malaysia, New Caledonia, Norfolk Island, Niue, Nepal, Nauru, Pakistan, Pitcairn Islands, Philippines, Palau, Papua New Guinea, North Korea, French Polynesia, Singapore, Solomon Islands, Thailand, Tokelau, Timor-Leste, Tonga, Tuvalu, U.S. Outlying Islands, Vietnam, Vanuatu, Wallis & Futuna, Samoa
REF	Countries from the Reforming Economies of the Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
SSA	Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo-Brazzaville, Congo-Kinshasa, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, São Tomé & Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, St. Helena, Tanzania, Togo, Uganda, Zambia, Zimbabwe
USA	USA	USA

S2.1.2 Results section 5-region aggregation

A map of this aggregation is shown in main paper Figure 4, panel b).

Table S2: REMIND 5-region aggregation based on REMIND "H12" 12-region aggregation

5-region name	H12 codes	H12 names	Full list of countries
OECD	CAZ; EUR; JPN; NEU; USA	Canada, NZ, Australia; EU 28; Japan; Non-EU28 Europe; USA	Åland Islands, Albania, Andorra, Australia, Austria, Belgium, Bosnia & Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czechia, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Guernsey, Heard & McDonald Islands, Hungary, Iceland, Ireland, Isle of Man, Italy, Japan, Jersey, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Montenegro, Netherlands, New Zealand, North Macedonia, Norway, Poland, Portugal, Romania, San Marino, Serbia, Slovakia, Slovenia, Spain, St. Pierre & Miquelon, Svalbard & Jan Mayen, Sweden, Switzerland, Turkey, United Kingdom, USA, Vatican City
China	CHA	China	China, Hong Kong, Macau, Taiwan
S & SE Asia	IND; OAS	India; Other Asia	Afghanistan, American Samoa, Bangladesh, Bhutan, British Indian Ocean Territory, Brunei, Cambodia, Christmas Island, Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, French Southern Territories, Guam, India, Indonesia, Kiribati, Laos, Malaysia, Maldives, Marshall Islands, Micronesia (Federated States of), Mongolia, Myanmar (Burma), Nauru, Nepal, New Caledonia, Niue, Norfolk Island, North Korea, Northern Mariana Islands, Pakistan, Palau, Papua New Guinea, Philippines, Pitcairn Islands, Samoa, Singapore, Solomon Islands, South Korea, Sri Lanka, Thailand, Timor-Leste, Tokelau, Tonga, Tuvalu, U.S. Outlying Islands, Vanuatu, Vietnam, Wallis & Futuna
Rest of the World	LAM; MEA; REF	Latin America and the Caribbean; Middle East, North Africa, Central Asia; Countries from the Reforming Economies of the Former Soviet Union	Algeria, Anguilla, Antarctica, Antigua & Barbuda, Argentina, Armenia, Aruba, Azerbaijan, Bahamas, Bahrain, Barbados, Belarus, Belize, Bermuda, Bolivia, Bouvet Island, Brazil, British Virgin Islands, Caribbean Netherlands, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Falkland Islands, French Guiana, Georgia, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Iran, Iraq, Israel, Jamaica, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lebanon, Libya, Martinique, Mexico, Moldova, Montserrat, Morocco, Nicaragua, Oman, Palestinian Territories, Panama, Paraguay, Peru, Puerto Rico, Qatar, Russia, Saudi Arabia, Sint Maarten, South Georgia & South Sandwich Islands, St. Barthélemy, St. Kitts & Nevis, St. Lucia, St. Martin, St. Vincent & Grenadines, Sudan, Suriname, Syria, Tajikistan, Trinidad & Tobago, Tunisia, Turkmenistan, Turks & Caicos Islands, U.S. Virgin Islands, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Venezuela, Western Sahara, Yemen

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Table S2: REMIND 5-region aggregation based on REMIND "H12" 12-region aggregation (continued)

5-region name	H12 codes	H12 names	Full list of countries
Sub-Saharan Africa	SSA	Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo-Brazzaville, Congo-Kinshasa, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, São Tomé & Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, St. Helena, Tanzania, Togo, Uganda, Zambia, Zimbabwe

S2.2 Plastics

S2.2.1 Flowchart

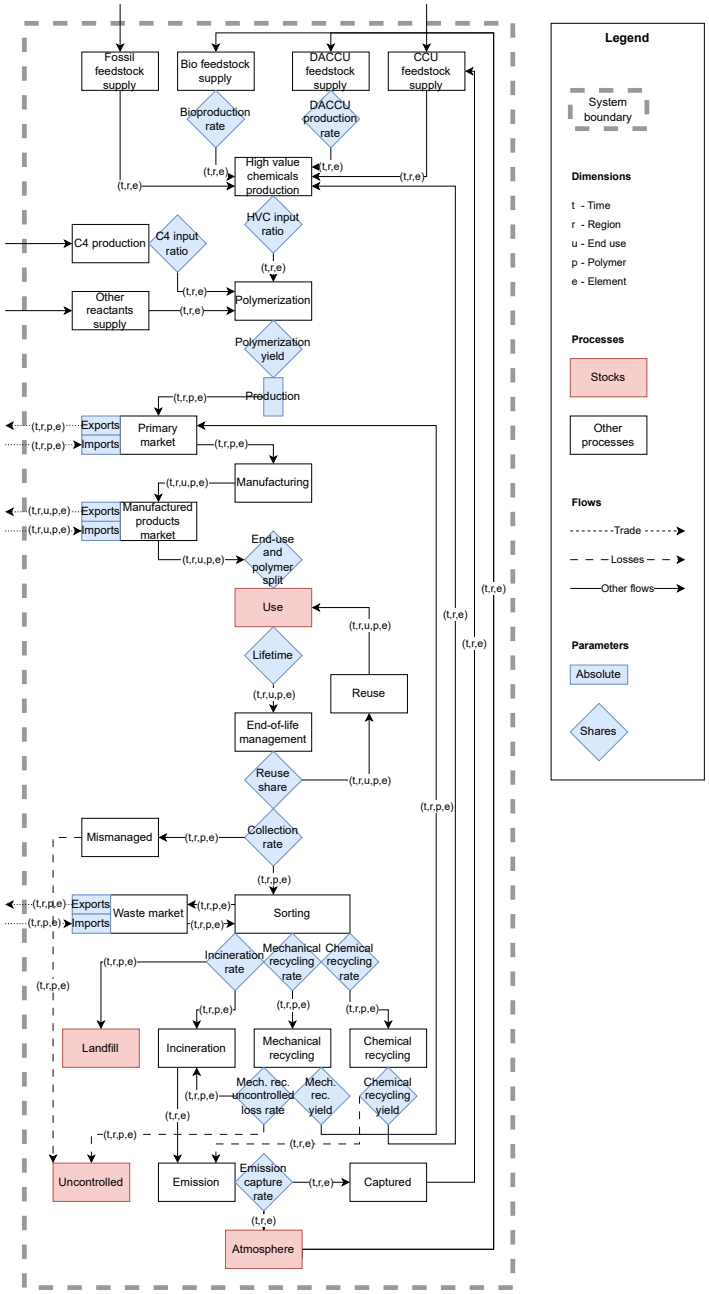


Figure S2: Flowchart of the prospective plastics MFA system (cf. main paper Figure 3, panel a).

S2.2.2 Dimensions

Table S3: Plastics Dimensions

Name	Letter	Items
Time	t	1950 to 2100
Historical Time	h	1950 to 2024
Region	r	*see region definition*
Element	e	C, Other Elements
Polymer	p	HDPE, LDPE, PET, PP, PS, PVC, PUR, Other thermoplastics, Rubbers, Polyamide fibre, PET fibre, Other fibre, Other thermosets
Polymer Type	P	Plastics, Fibre, Rubber
End Use	u	Buildings & Construction, Consumer & Institutional, Electrical/Electronics, Industrial Machinery, Packaging, Textile sector, Transportation, Others
Driver Scenario	S	SSP1, SSP2, SSP3, SSP4, SSP5

S2.2.3 Processes

Table S4: Plastics Processes

Name
sysenv
feedfoss
feedbio
feeddaccu
feedccu
hvc_production
c4_production
polymerization
primary_market
manufacturing
manufactured_products_market
use
eol_management
reuse
waste_market
reclmech
reclchem
incineration
landfill
sorting
mismanaged
uncontrolled
emission
captured
atmosphere
other_reactants
losses
aux_recyclate_market
aux_recl_feedstock_market

Continued on next page

Table S4: Plastics Processes (continued)

Name
imports
exports

S2.2.4 Flows

Table S5: Plastics Flows

Dimensions	Origin Process	Destination Process
t, e, r	sysenv	feedfoss
t, e, r	sysenv	feedccu
t, e, r	exports	sysenv
t, e, r	sysenv	imports
t, e, r	sysenv	c4_production
t, e, r	sysenv	other_reactants
t, e, r	losses	sysenv
t, e, r	atmosphere	feedbio
t, e, r	atmosphere	feeddaccu
t, e, r	feedfoss	hvc_production
t, e, r	feedbio	hvc_production
t, e, r	feeddaccu	hvc_production
t, e, r	feedccu	hvc_production
t, e, r	hvc_production	polymerization
t, e, r	c4_production	polymerization
t, e, r	other_reactants	polymerization
t, e, r, p	polymerization	primary_market
t, e, r	polymerization	losses
t, e, r, p	primary_market	manufacturing
t, e, r, p	primary_market	exports
t, e, r, p	imports	primary_market
t, e, r, p, u	manufacturing	manufactured_products_market
t, e, r, p, u	manufactured_products_market	use
t, e, r, p, u	manufactured_products_market	exports
t, e, r, p, u	imports	manufactured_products_market
t, e, r, p, u	use	eol_management
t, e, r, p, u	eol_management	reuse
t, e, r, p, u	reuse	use
t, e, r, p	eol_management	sorting
t, e, r, p	eol_management	mismanaged
t, e, r, p	sorting	reclmech
t, e, r, p	sorting	reclchem
t, e, r, p	sorting	landfill
t, e, r, p	sorting	incineration
t, e, r, p	mismanaged	uncontrolled
t, e, r, p	reclmech	aux_recyclate_market
t, e, r, p	aux_recyclate_market	primary_market
t, e, r	reclchem	aux_recl_feedstock_market
t, e, r	aux_recl_feedstock_market	hvc_production
t, e, r	reclchem	emission
t, e, r, p	reclmech	uncontrolled

Continued on next page

Table S5: Plastics Flows (continued)

Dimensions	Origin Process	Destination Process
t, e, r, p	reclmech	incineration
t, e, r	incineration	emission
t, e, r	emission	captured
t, e, r	emission	atmosphere
t, e, r	captured	feedccu
t, e, r, p	waste_market	sorting
t, e, r, p	sorting	waste_market
t, e, r, p	waste_market	exports
t, e, r, p	imports	waste_market
t, e, r, p	aux_recyclate_market	exports
t, e, r, p	imports	aux_recyclate_market
t, e, r	aux_recl_feedstock_market	exports
t, e, r	imports	aux_recl_feedstock_market

S2.2.5 Stocks

Table S6: Plastics Stocks

Dimensions	Name	Process	Stock Type	Lifetime Model
t, r, u	use_dsm		InflowDrivenDSM	LogNormalLifetime
t, e, r, p, u	use	use	SimpleFlowDrivenStock	
t, e, r	atmospheric	atmosphere	SimpleFlowDrivenStock	
t, e, r, p	landfill	landfill	SimpleFlowDrivenStock	
t, e, r, p	uncontrolled	uncontrolled	SimpleFlowDrivenStock	

S2.2.6 Trades

Table S7: Plastics Trades

Dimensions	Name
t, r, p	primary
t, r, p, u	manufactured_products
t, e, r, p	waste
t, e, r, p	aux_recyclate
t, e, r	aux_recl_feedstock

S2.2.7 Parameters

Table S8: Plastics Parameters

Dimensions	Name	Description	Sources
h, r	collection_rate	Collection rate of plastic waste	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Jiang et al. 2020, Yonggang et al. 2024, Hunan Yinghong New Materials Co., Ltd. 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, OECD 2022a, OECD 2022b, Plastics Europe 2025, US EPA 2017
h, r	mechanical_recycling_rate	Mechanical recycling rate of collected waste	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Jiang et al. 2020, Yonggang et al. 2024, Hunan Yinghong New Materials Co., Ltd. 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, OECD 2022a, OECD 2022b, Plastics Europe 2025, US EPA 2017
	chemical_recycling_rate	Chemical recycling rate of collected waste	
h, r	incineration_rate	Incineration rate of collected waste	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Jiang et al. 2020, Yonggang et al. 2024, Hunan Yinghong New Materials Co., Ltd. 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, OECD 2022a, OECD 2022b, Plastics Europe 2025, US EPA 2017
h, r, P, p	primary_imports	Historical primary plastics imports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, IRSG 2026, OECD 2022a, OECD 2022b, Plastics Europe 2025, Ren et al. 2025, Textile Exchange 2026, Industrievereinigung Chemiefaser e.V. (IVC) 2025, UNCTAD 2025b
h, r, P, p	primary_exports	Historical primary plastics exports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, IRSG 2026, OECD 2022a, OECD 2022b, Plastics Europe 2025, Ren et al. 2025, Textile Exchange 2026, Industrievereinigung Chemiefaser e.V. (IVC) 2025, UNCTAD 2025b

Continued on next page

Table S8: Plastics Parameters (continued)

Dimensions	Name	Description	Sources
h, r, P, p, u	manufactured_products_imports	Historical manufactured products imports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, IRSG 2026, OECD 2022a, OECD 2022b, Plastics Europe 2025, Ren et al. 2025, Textile Exchange 2026, Industrievereinigung Chemiefaser e.V. (IVC) 2025, UNCTAD 2025b
h, r, P, p, u	manufactured_products_exports	Historical manufactured products exports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, IRSG 2026, OECD 2022a, OECD 2022b, Plastics Europe 2025, Ren et al. 2025, Textile Exchange 2026, Industrievereinigung Chemiefaser e.V. (IVC) 2025, UNCTAD 2025b
h, r, P, p	waste_imports	Historical plastic waste imports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, IRSG 2026, OECD 2022a, OECD 2022b, Plastics Europe 2025, Ren et al. 2025, Textile Exchange 2026, Industrievereinigung Chemiefaser e.V. (IVC) 2025, UNCTAD 2025b
h, r, P, p	waste_exports	Historical plastic waste exports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, IRSG 2026, OECD 2022a, OECD 2022b, Plastics Europe 2025, Ren et al. 2025, Textile Exchange 2026, Industrievereinigung Chemiefaser e.V. (IVC) 2025, UNCTAD 2025b
	bio_production_rate	Share of bio-based HVC production	
	daccu_production_rate	Share of DACCU HVC production	
p, e	hvc_input_shares	Share of HVC in total polymerization input	Levi and Cullen 2018
p, e	c4_input_shares	Share of C4 in total polymerization input	Levi and Cullen 2018
p	polymerization_yield	Polymerization yield	Levi and Cullen 2018
	mechanical_recycling_yield	Yield of mechanical recycling	Uekert et al. 2023

Continued on next page

Table S8: Plastics Parameters (continued)

Dimensions	Name	Description	Sources
	reclmech_loss_uncontrolled_rate	Rate of mechanical recycling losses to uncontrolled disposal	Brown et al. 2023
	chemical_recycling_yield	Yield of chemical recycling	Yadav et al. 2023
	emission_capture_rate	Carbon capture rate for emissions of incinerated plastics	
e, p	carbon_content_polymers	Carbon content of polymers	Carbon contents of different polymers are calculated from their chemical structure. For broader categories (Other thermoplastics, other thermosets), rough assumptions and weighted averages were used.
h, r, P	production	Historical plastic production, differentiated by polymer type (Fibre/Rubber/Plastics)	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, IRSG 2026, OECD 2022a, OECD 2022b, Plastics Europe 2025, Ren et al. 2025, Textile Exchange 2026, Industrievereinigung Chemiefaser e.V. (IVC) 2025
h, r, P, p, u	end_use_polymer_split	Share of each polymer and end-use within total Fibre/Rubber/Plastics apparent consumption per region	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, Gao and Cabrera Serrenho 2023, Gao and Cabrera Serrenho 2025, Geyer, Jambeck, and Law 2017, IRSG 2026, OECD 2022a, OECD 2022b, Plastics Europe 2025, Ren et al. 2025, Textile Exchange 2026, Industrievereinigung Chemiefaser e.V. (IVC) 2025
u	lifetime_mean	Mean lifetime of final products	Geyer, Jambeck, and Law 2017
u	lifetime_std	Standard deviation of lifetime	Geyer, Jambeck, and Law 2017
t, r, S	population	Population	International Monetary Fund 2021, India Department of Economic Affairs n.d., India Ministry of Health 2019, IIASA 2024, James et al. 2012, Arujo et al. 2021, World Bank 2023a, IIASA 2024, Crespo Cuaresma 2017, Dellink et al. 2017, KC et al. 2024, United Nations, Department on Economic and Social Affairs, Population Division 2022, World Bank 2023b, Gapminder 2025

Continued on next page

Table S8: Plastics Parameters (continued)

Dimensions	Name	Description	Sources
t, r, S	gdppc	GDP per capita	International Monetary Fund 2021, India Department of Economic Affairs n.d., India Ministry of Health 2019, IIASA 2024, James et al. 2012, Arujo et al. 2021, World Bank 2023a, IIASA 2024, Crespo Cuaresma 2017, Dellink et al. 2017, KC et al. 2024, United Nations, Department on Economic and Social Affairs, Population Division 2022, World Bank 2023b, Gapminder 2025, Bolt, Timmer, and Van Zanden 2014

S2.3 Steel

S2.3.1 Flowchart

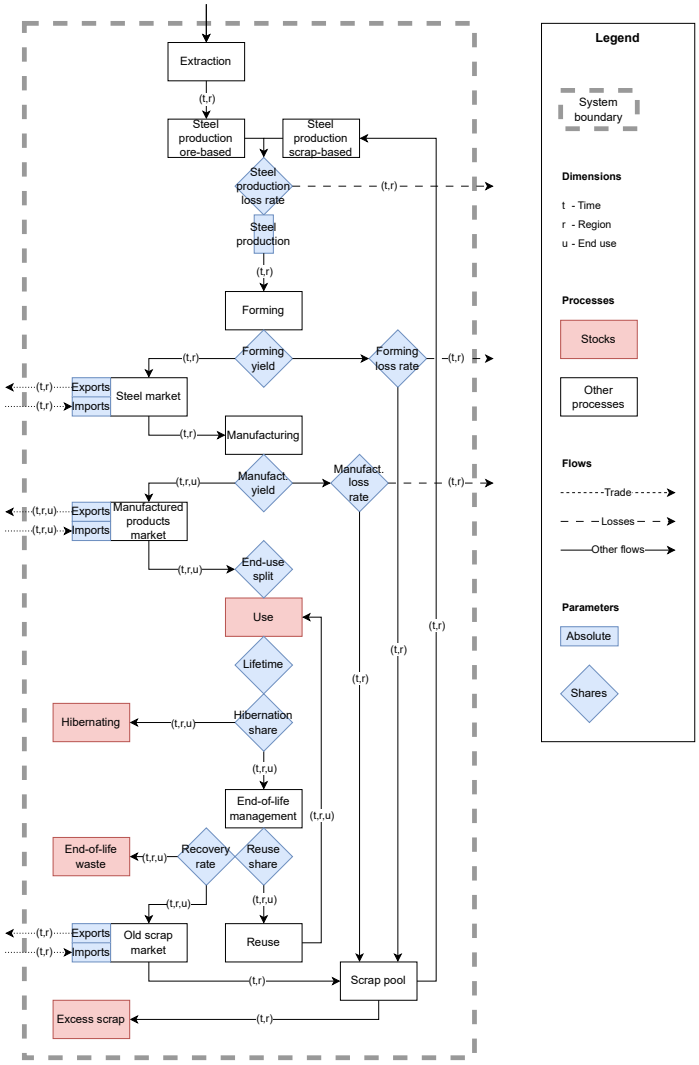


Figure S3: Flowchart of the prospective steel MFA system (cf. main paper Figure 3, panel b).

S2.3.2 Dimensions

Table S9: Steel Dimensions

Name	Letter	Items
Time	t	1900 to 2100
Historical Time	h	1900 to 2022
Region	r	*see region definition*
End Use	u	Construction, Machinery, Products, Transport
Driver Scenario	S	SSP1, SSP2, SSP3, SSP4, SSP5

S2.3.3 Processes

Table S10: Steel Processes

Name
sysenv
steel_production_ore_based
steel_production_scrap_based
forming
steel_market
manufacturing
manufactured_products_market
use
hibernating
eol_management
reuse
eol_waste
scrap_market
scrap_pool
excess_scrap
imports
exports
losses
extraction

S2.3.4 Flows

Table S11: Steel Flows

Dimensions	Origin Process	Destination Process
t, r	extraction	steel_production_ore_based
t, r	steel_production_ore_based	forming
t, r	steel_production_ore_based	losses
t, r	scrap_pool	steel_production_scrap_based
t, r	steel_production_scrap_based	forming
t, r	steel_production_scrap_based	losses
t, r	forming	steel_market
t, r	forming	scrap_pool
t, r	forming	losses
t, r	manufacturing	losses

Continued on next page

Table S11: Steel Flows (continued)

Dimensions	Origin Process	Destination Process
t, r	steel_market	manufacturing
t, r	steel_market	exports
t, r	imports	steel_market
t, r, u	manufacturing	manufactured_products_market
t, r	manufacturing	scrap_pool
t, r, u	manufactured_products_market	exports
t, r, u	imports	manufactured_products_market
t, r, u	manufactured_products_market	use
t, r, u	use	hibernating
t, r, u	use	eol_management
t, r, u	eol_management	reuse
t, r, u	reuse	use
t, r, u	eol_management	scrap_market
t, r, u	eol_management	eol_waste
t, r	scrap_market	scrap_pool
t, r	scrap_market	exports
t, r	imports	scrap_market
t, r	scrap_pool	excess_scrap
t, r	exports	sysenv
t, r	sysenv	imports
t, r	losses	sysenv
t, r	sysenv	extraction

S2.3.5 Stocks

Table S12: Steel Stocks

Dimensions	Name	Process	Stock Type	Lifetime Model
t, r, u	use	use	InflowDrivenDSM	LogNormalLifetime
t, r, u	hibernating	hibernating	SimpleFlowDrivenStock	
t, r, u	eol_waste	eol_waste	SimpleFlowDrivenStock	
t, r	excess_scrap	excess_scrap	SimpleFlowDrivenStock	

S2.3.6 Trades

Table S13: Steel Trades

Dimensions	Name
t, r	steel
t, r, u	manufactured_products
t, r	scrap

S2.3.7 Parameters

Table S14: Steel Parameters

Dimensions	Name	Description	Sources
	forming_yield	Yield of steel forming process	Cullen, Allwood, and Bambach 2012
u	manufacturing_yield	Yield during manufacturing of steel-containing final products	Cullen, Allwood, and Bambach 2012
u	recovery_rate	Combined collection and recovery rate at end-of-life - share of all end-of life material that is recycled	World Steel Association 2025a, World Steel Association 2021, *Raw materials* 2026
t, r, S	population	Population	International Monetary Fund 2021, India Department of Economic Affairs n.d., India Ministry of Health 2019, IIASA 2024, James et al. 2012, Arujo et al. 2021, World Bank 2023a, IIASA 2024, Crespo Cuaresma 2017, Dellink et al. 2017, KC et al. 2024, United Nations, Department on Economic and Social Affairs, Population Division 2022, World Bank 2023b, Gapminder 2025
t, r, S	gdppc	GDP per capita	International Monetary Fund 2021, India Department of Economic Affairs n.d., India Ministry of Health 2019, IIASA 2024, James et al. 2012, Arujo et al. 2021, World Bank 2023a, IIASA 2024, Crespo Cuaresma 2017, Dellink et al. 2017, KC et al. 2024, United Nations, Department on Economic and Social Affairs, Population Division 2022, World Bank 2023b, Gapminder 2025, Bolt, Timmer, and Van Zanden 2014
u	lifetime_mean	Mean lifetime of Products	Cooper and Allwood 2012
u	lifetime_std	Absolute standard deviation of final product lifetime	Cooper and Allwood 2012
u	end_use_split_low_inco	End use shares in consumption for low gdp per capita	Pauliuk et al. 2013
u	end_use_split_medium_inco	End use shares in consumption for medium gdp per capita	
u	end_use_split_high_inco	End use shares in consumption for high gdp per capita	Pauliuk et al. 2013
	end_use_split_gdppc_low	Upper GDP per capita threshold for end_use_split_low_inco	

Continued on next page

Table S14: Steel Parameters (continued)

Dimensions	Name	Description	Sources
	end_use_split_gdppc_high	Lower GDP per capita threshold for end_use_split_high_inco	
	forming_loss_rate	Loss rate in forming process. Contrary to (1-forming_yield), this material is completely lost and not recycled as home scrap	Cullen, Allwood, and Bambach 2012
	steel_production_loss_rate	Loss rate of iron and raw steel production in BF-BOF and (DRI-)EAF processes	Cullen, Allwood, and Bambach 2012
h, r	scrap_consumption	Historical scrap consumption	Bureau of International Recycling AISBL 2009–2024, World Steel Association 2023b, World Steel Association 2023a, World Steel Association 2025b
h, r	scrap_consumption_no_assumptions	Historical scrap consumption	Bureau of International Recycling AISBL 2009–2024, World Steel Association 2023b, World Steel Association 2023a, World Steel Association 2025b
h, r	steel_production	Historical steel production	World Steel Association 2023b, World Steel Association 2023a, World Steel Association 2025b
h, r	steel_imports	Historical steel imports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, World Steel Association 2023b, World Steel Association 2023a, World Steel Association 2025b
h, r	steel_exports	Historical steel exports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, World Steel Association 2023b, World Steel Association 2023a, World Steel Association 2025b
h, r, u	manufactured_products_imports	Historical imports of steel contained in manufactured products	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, World Steel Association 2023b, World Steel Association 2023a, World Steel Association 2025b
h, r, u	manufactured_products_exports	Historical exports of steel contained in manufactured products	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, World Steel Association 2023b, World Steel Association 2023a, World Steel Association 2025b
h, r	scrap_imports	Historical combined eol product and scrap imports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, World Steel Association 2023b, World Steel Association 2023a, World Steel Association 2025b

Continued on next page

Table S14: Steel Parameters (continued)

Dimensions	Name	Description	Sources
h, r	scrap_exports	Historical combined eol product and scrap exports	Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, World Steel Association 2023b, World Steel Association 2023a, World Steel Association 2025b

S2.4 Cement

S2.4.1 Flowchart

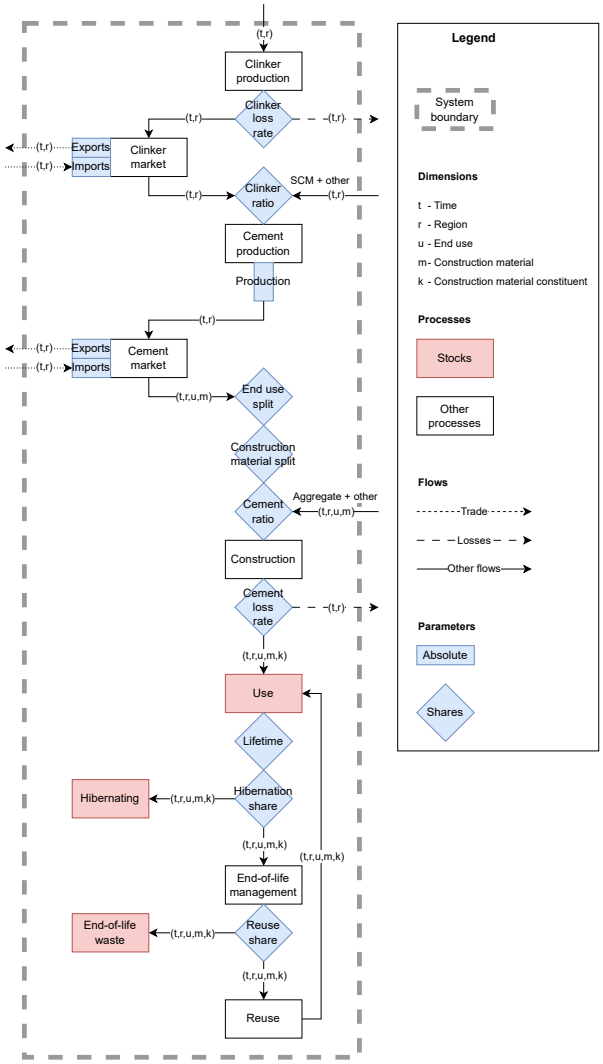


Figure S4: Flowchart of the prospective cement MFA system (cf. main paper Figure 3, panel c).

S2.4.2 Dimensions

Table S15: Cement Dimensions

Name	Letter	Items
Time	t	1880 to 2100
Historical Time	h	1880 to 2025
Region	r	*see region definition*
End Use	u	Residential, Commercial, Industrial, Civil Engineering
Construction Material	m	Concrete, Mortar
Construction Material Constituent	k	Cement, Non-Cement
Driver Scenario	S	SSP1, SSP2, SSP3, SSP4, SSP5

S2.4.3 Processes

Table S16: Cement Processes

Name
sysenv
clinker_production
clinker_market
cement_production
cement_market
construction
use
hibernating
eol_management
eol_waste
reuse
losses
imports
exports

S2.4.4 Flows

Table S17: Cement Flows

Dimensions	Origin Process	Destination Process
t, r	sysenv	clinker_production
t, r	clinker_production	clinker_market
t, r	clinker_production	losses
t, r	clinker_market	exports
t, r	imports	clinker_market
t, r	clinker_market	cement_production
t, r	sysenv	cement_production
t, r	cement_production	cement_market
t, r	cement_market	exports
t, r	imports	cement_market

Continued on next page

Table S17: Cement Flows (continued)

Dimensions	Origin Process	Destination Process
t, r, u, m	cement_market	construction
t, r, u, m	sysenv	construction
t, r, u, m, k	construction	use
t, r	construction	losses
t, r, u, m, k	use	hibernating
t, r, u, m, k	use	eol_management
t, r, u, m, k	eol_management	reuse
t, r, u, m, k	reuse	use
t, r, u, m, k	eol_management	eol_waste
t, r	losses	sysenv
t, r	exports	sysenv
t, r	sysenv	imports

S2.4.5 Stocks

Table S18: Cement Stocks

Dimensions	Name	Process	Stock Type	Lifetime Model
t, r, u, m, k	use	use	InflowDrivenDSM	LogNormalLifetime
t, r, u, m, k	hibernating	hibernating	SimpleFlowDrivenStock	
t, r, u, m, k	eol_waste	eol_waste	SimpleFlowDrivenStock	

S2.4.6 Trades

Table S19: Cement Trades

Dimensions	Name
t, r	clinker
t, r	cement

S2.4.7 Parameters

Table S20: Cement Parameters

Dimensions	Name	Description	Sources
r, u	end_use_split	Split of cement production into different end uses.	R. Andrew 2026, Xi et al. 2016
h, r	cement_production	Historical cement production volume for each region and year.	R. Andrew 2026
h, r	clinker_ratio	Historical clinker-to-cement ratio for each region.	R. M. Andrew 2026, R. Andrew 2026, Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, GCCA 2024, U.S. Geological Survey 2024
h, r, u	lifetime_mean	Mean lifetime of historical cement stocks by region and end use.	R. Andrew 2026, *posted: lifetimes branch* 2026, BPIE and UCL 2022, Cao, Shen, et al. 2017, Cao, Liu, et al. 2019, Cao, Masanet, et al. 2021, Deetman et al. 2020, Hatayama et al. 2010, Kapur et al. 2008, Sandberg et al. 2016, Wiedenhofer et al. 2024
	lifetime_rel_std	Relative standard deviation of lifetime of cement in buildings and infrastructure.	Expert guess
h, r	clinker_imports	Historical clinker imports for each region and year.	R. Andrew 2026, Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, U.S. Geological Survey 2024
h, r	clinker_exports	Historical clinker exports for each region and year.	R. Andrew 2026, Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, U.S. Geological Survey 2024
h, r	cement_imports	Historical cement imports for each region and year.	R. Andrew 2026, Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, U.S. Geological Survey 2024
h, r	cement_exports	Historical cement exports for each region and year.	R. Andrew 2026, Gaulier and Zignago 2010, UNCTAD 2025a, UNEP 2020, U.S. Geological Survey 2024
t, r, S	population	Historical and projected population for each region and model year.	International Monetary Fund 2021, India Department of Economic Affairs n.d., India Ministry of Health 2019, IIASA 2024, James et al. 2012, Arujo et al. 2021, World Bank 2023a, IIASA 2024, Crespo Cuaresma 2017, Dellink et al. 2017, KC et al. 2024, United Nations, Department on Economic and Social Affairs, Population Division 2022, World Bank 2023b, Gapminder 2025

Continued on next page

Table S20: Cement Parameters (continued)

Dimensions	Name	Description	Sources
t, r, S	gdppc	Historical and projected GDP per capita for each region and model year.	International Monetary Fund 2021, India Department of Economic Affairs n.d., India Ministry of Health 2019, IIASA 2024, James et al. 2012, Arujo et al. 2021, World Bank 2023a, IIASA 2024, Crespo Cuaresma 2017, Dellink et al. 2017, KC et al. 2024, United Nations, Department on Economic and Social Affairs, Population Division 2022, World Bank 2023b, Gapminder 2025, Bolt, Timmer, and Van Zanden 2014
	cement_losses	Share of cement lost during construction.	Kaufmann et al. 2024
	clinker_losses	Share of clinker lost during clinker production.	Kaufmann et al. 2024
r, m	cement_ratio	Mass share of cement in each newly produced construction material.	R. Andrew 2026, Kaufmann et al. 2024
r, m	construction_material_split	Share of cement used in each construction material by region.	R. Andrew 2026, Kaufmann et al. 2024

S2.5 Bibliography

References

Andrew, Robbie (Aug. 2026). *Annual global cement production data*. Version 260831. Zenodo. DOI: 10.5281/zenodo.22207852. URL: https://doi.org/10.5281/zenodo.22207852.

Andrew, Robbie M. (2026). *Global CO2 emissions from cement production (Version 260830) [Data set]*. en. DOI: https://doi.org/10.5281/zenodo.22178444. URL: https://zenodo.org/records/22178444.

Arujo, Ewerton, Benjamin Leon Bodirsky, Michael S. Crawford, Debbora Leip, and Jan Dietrich (Jan. 2021). *MissingIslands dataset for filling in data gaps from the WDI datasets*. DOI: 10.5281/ZENODO.4421504. URL: https://zenodo.org/record/4421504 (visited on 11/26/2025).

Bolt, Jutta, Marcel Timmer, and Jan Luiten Van Zanden (Oct. 2, 2014). "GDP per capita since 1820". In: *How Was Life?: Global Well-being since 1820*. OECD. ISBN: 978-92-64-21406-4. DOI: 10.1787/9789264214262-en. URL: https://www.oecd.org/en/publications/how-was-life_9789264214262-en.html (visited on 12/16/2025).

BPIE and UCL (2022). *2022 Global Status Report for Buildings and Construction*. Tech. rep. United Nations Environment Programme (UNEP). (Visited on 05/03/2025).

Brown, Erina, Anna MacDonald, Steve Allen, and Deonie Allen (May 2023). "The potential for a plastic recycling facility to release microplastic pollution and possible filtration remediation effectiveness". In: *Journal of Hazardous Materials Advances* 10, p. 100309. ISSN: 27724166. DOI: 10.1016/j.hazadv.2023.100309. URL: https://linkinghub.elsevier.com/retrieve/pii/S2772416623000803 (visited on 12/19/2025).

Bureau of International Recycling AISBL, Ferrous Division (2009–2024). *World Steel Recycling in Figures. Recycled Steel – a Raw Material for Green Steelmaking*. Digitalized by hand. Brussels, Belgium: Bureau of International Recycling. URL: https://www.bir.org/en/publications/facts-figures (visited on 09/19/2026).

Cao, Zhi, Gang Liu, Huabo Duan, Fengming Xi, Guiwen Liu, and Wei Yang (Mar. 2019). "Unravelling the Mystery of Chinese Building Lifetime: A Calibration and Verification Based on Dynamic Material Flow Analysis". In: *Applied Energy* 238, pp. 442–452. ISSN: 03062619. DOI: 10.1016/j.apenergy.2019.01.106. (Visited on 04/03/2025).

Cao, Zhi, Eric Masanet, Anupam Tiwari, and Sahil Akolawala (Mar. 2021). *Decarbonizing Concrete: Deep Decarbonization Pathways for the Cement and Concrete Cycle in the United States, India, and China*. Tech. rep. Industrial Sustainability Analysis Laboratory.

Cao, Zhi, Lei Shen, Amund N. Løvik, Daniel B. Müller, and Gang Liu (Oct. 2017). "Elaborating the History of Our Cementing Societies: An in-Use Stock Perspective". In: *Environmental Science & Technology* 51.19, pp. 11468–11475. ISSN: 0013-936X. DOI: 10.1021/acs.est.7b03077. (Visited on 03/28/2025).

Cooper, Daniel R. and Julian M. Allwood (Sept. 2012). "Reusing Steel and Aluminum Components at End of Product Life". In: *Environmental Science & Technology* 46.18. Publisher: American Chemical Society, pp. 10334–10340. ISSN: 0013-936X. DOI: 10.1021/es301093a. URL: https://doi.org/10.1021/es301093a (visited on 12/16/2025).

Crespo Cuaresma, Jesús (Jan. 2017). "Income projections for climate change research: A framework based on human capital dynamics". en. In: *Global Environmental Change* 42, pp. 226–236. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2015.02.012. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378015000382 (visited on 11/26/2025).

Cullen, Jonathan M., Julian M. Allwood, and Margarita D. Bambach (Dec. 2012). "Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods". In: *Environmental Science & Technology* 46.24. Publisher: American Chemical Society, pp. 13048–13055. ISSN: 0013-936X. DOI: 10.1021/es302433p. URL: https://doi.org/10.1021/es302433p (visited on 12/16/2025).

Deetman, Sebastiaan, Sylvia Marinova, Ester Van Der Voet, Detlef P. Van Vuuren, Oreane Edelenbosch, and Reinout Heijungs (Feb. 2020). "Modelling Global Material Stocks and Flows for Residential and Service Sector Buildings towards 2050". In: *Journal of Cleaner Production* 245, p. 118658. ISSN: 09596526. DOI: 10.1016/j.jclepro.2019.118658. (Visited on 03/04/2025).

Dellink, Rob, Jean Chateau, Elisa Lanzi, and Bertrand Magné (Jan. 2017). "Long-term economic growth projections in the Shared Socioeconomic Pathways". In: *Global Environmental Change* 42, pp. 200–214. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2015.06.004. URL: https://www.sciencedirect.com/science/article/pii/S0959378015000837 (visited on 11/26/2025).

Gao, Yunhu and André Cabrera Serrenho (2023). "Matlab code for "Evaluating the potential to reduce the global demand for virgin plastics, fibres and rubbers"". In: DOI: 10.17863/CAM.101645. URL: https://www.repository.cam.ac.uk/handle/1810/357881.

— (Sept. 2025). "Evaluating the potential to reduce the global demand for polymers". In: *Resources, Conservation and Recycling* 223, p. 108518. ISSN: 0921-3449. DOI: 10.1016/j.resconrec.2025.108518. URL: https://www.sciencedirect.com/science/article/pii/S0921344925003969 (visited on 03/12/2026).

Gapminder (2025). *Population*. URL: https://www.gapminder.org/data/documentation/gd003/ (visited on 12/16/2025).

Gaulier, Guillaume and Soledad Zignago (Oct. 2010). *BACI: International Trade Database at the Product-Level. The 1994-2007 Version*. Working Papers 2010-23. CEPII. URL: https://www.cepii.fr/CEPII/fr/publications/wp/abstract.asp?NoDoc=2726.

GCCA (2024). *GCCA GNR Data for 92AGW - Clinker to Cementitious Ratio*. (Visited on 01/21/2025).

Geyer, Roland, Jenna R. Jambeck, and Kara Lavender Law (July 2017). "Production, use, and fate of all plastics ever made". en. In: *Science Advances* 3.7, e1700782. ISSN: 2375-2548. DOI: 10.1126/sciadv.1700782. URL: https://www.science.org/doi/10.1126/sciadv.1700782 (visited on 11/29/2024).

Hatayama, Hiroki, Ichiro Daigo, Yasunari Matsuno, and Yoshihiro Adachi (Aug. 2010). "Outlook of the World Steel Cycle Based on the Stock and Flow Dynamics". In: *Environmental Science & Technology* 44.16, pp. 6457–6463. ISSN: 0013-936X. DOI: 10.1021/es100044n. (Visited on 04/04/2025).

Hunan Yinghong New Materials Co., Ltd. (Apr. 2020). *Authoritative release: In 2019, China recycled 18.9 million tonnes of waste plastic, with a recycling rate of 30 % — Yinghong New Materials*. URL: http://www.hnyhgf.com/news/20200407155356431.html (visited on 10/23/2025).

IIASA (2024). *Socioeconomic Projections of the Shared Socioeconomic Pathways (SSPs), hosted by IIASA*. URL: https://data.ece.iiasa.ac.at/ssp.

India Department of Economic Affairs (n.d.). *Department of Economic Affairs (DEA) projections FY 2024-25 to FY 2047-48*.

India Ministry of Health (Nov. 2019). *PopulationProjections for India and States 2011 – 2036*. URL: https://nhm.gov.in/New_Updates_2018/Report_Population_Projection_2019.pdf.

Industrievereinigung Chemiefaser e.V. (IVC) (2025). *Chemiefaserproduktion nach Regionen*. URL: https://www.ivc-ev.de/de/chemiefaserproduktion-nach-regionen-balkendiagramm (visited on 08/03/2026).

International Monetary Fund (Oct. 2021). *World Economic Outlook database of the IMF*. URL: https://www.imf.org/-/media/Files/Publications/WEO/WEO-Database/2021/WEOOct2021all.ashx.

IRSG (2026). *International Rubber Study Group*. URL: https://www.rubberstudy.org/welcome (visited on 07/24/2026).

James, Spencer L, Paul Gubbins, Christopher Jl Murray, and Emmanuela Gakidou (Dec. 2012). "Developing a comprehensive time series of GDP per capita for 210 countries from 1950 to 2015". In: *Population Health Metrics* 10.1, p. 12. ISSN: 1478-7954. DOI: 10.1186/1478-7954-10-12. URL: https://pophealthmetrics.biomedcentral.com/articles/10.1186/1478-7954-10-12 (visited on 11/26/2025).

Jiang, Xiaobin, Tao Wang, Meng Jiang, Ming Xu, Yadong Yu, Baohua Guo, Dingjiang Chen, Shanying Hu, Jian Jiang, Yupeng Zhang, and Bing Zhu (Oct. 2020). "Assessment of Plastic Stocks and Flows in China: 1978-2017". In: *Resources, Conservation and Recycling* 161, p. 104969. ISSN: 0921-3449. DOI: 10.1016/j.resconrec.2020.104969. URL: https://www.sciencedirect.com/science/article/pii/S0921344920302871 (visited on 06/24/2025).

Kapur, Amit, Gregory Keoleian, Alissa Kendall, and Stephen E. Kesler (2008). "Dynamic Modeling of In-Use Cement Stocks in the United States". In: *Journal of Industrial Ecology* 12.4, pp. 539–556. ISSN: 1530-9290. DOI: 10.1111/j.1530-9290.2008.00055.x. (Visited on 01/20/2025).

Kaufmann, Lisa, Dominik Wiedenhofer, Zhi Cao, Michaela Clarissa Theurl, Christian Lauk, André Baumgart, Simone Gingrich, and Helmut Haberl (Feb. 2024). "Society's material stocks as carbon pool: an economy-wide quantification of global carbon stocks from 1900–2015". In: *Environmental Research Letters* 19.2, p. 024051. ISSN: 1748-9326. DOI: 10.1088/1748-9326/ad236b. URL: http://dx.doi.org/10.1088/1748-9326/ad236b.

KC, Samir, Moradhvaj, Michaela Potancokova, Saroja Adhikari, Dilek Yildiz, Maria Mamolo, Tomas Sobotka, Krystof Zeman, Guy Abel, Wolfgang Lutz, and Anne Goujon (Feb. 2024). *Wittgenstein Center (WIC) Population and Human Capital Projections - 2023*. DOI: 10.5281/ZENODO.7767425. URL: https://zenodo.org/doi/10.5281/zenodo.7767425 (visited on 11/26/2025).

Levi, Peter G. and Jonathan M. Cullen (Feb. 2018). "Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products". In: *Environmental Science & Technology* 52.4. Publisher: American Chemical Society, pp. 1725–1734. ISSN: 0013-936X. DOI: 10.1021/acs.est.7b04573. URL: https://doi.org/10.1021/acs.est.7b04573 (visited on 12/01/2021).

OECD (Feb. 2022a). *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options*. en. OECD. ISBN: 978-92-64-58406-8. DOI: 10.1787/de747aef-en. URL: https://www.oecd.org/en/publications/global-plastics-outlook_de747aef-en.html (visited on 06/23/2025).

— (June 2022b). *Global Plastics Outlook: Policy Scenarios to 2060*. en. OECD. ISBN: 978-92-64-97364-0. DOI: 10.1787/aa1edf33-en. URL: https://www.oecd-ilibrary.org/environment/global-plastics-outlook_aa1edf33-en (visited on 04/18/2023).

Pauliuk, Stefan, Rachel L. Milford, Daniel B. Müller, and Julian M. Allwood (Apr. 2013). "The Steel Scrap Age". In: *Environmental Science & Technology* 47.7. Publisher: American Chemical Society, pp. 3448–3454. ISSN: 0013-936X. DOI: 10.1021/es303149z. URL: https://doi.org/10.1021/es303149z (visited on 09/06/2023).

Plastics Europe (Oct. 2025). *Knowledge hub • Plastics Europe*. en-GB. URL: https://plasticseurope.org/knowledge-hub/ (visited on 10/23/2025).

posted: lifetimes branch (2026). GitHub repository. Used for data processing. URL: https://github.com/bennet21/posted/tree/lifetimes.

Raw materials (June 2026). [Online; accessed 30. Sep. 2026]. URL: https://worldsteel.org/about-steel/raw-materials.

Ren, Yucheng, Hengzhi Zhu, Yuheng Cao, Xiaobin Jiang, Dingjiang Chen, Meng Jiang, Ming Xu, Baohua Guo, and Bing Zhu (Dec. 2025). "Dataset on the dynamic stocks and flows of 20 types of plastics in China, 1978–2022". en. In: *Scientific Data* 13.1. Publisher: Nature Publishing Group, p. 64. ISSN: 2052-4463. DOI: 10.1038/s41597-025-06363-0. URL: https://www.nature.com/articles/s41597-025-06363-0 (visited on 06/19/2026).

Sandberg, Nina Holck, Igor Sartori, Oliver Heidrich, Richard Dawson, Elena Dascalaki, Stella Dimitriou, Tomáš Vimm-r, Faidra Filippidou, Gašper Stegnar, Marjana Šijanec Zavrl, and Helge Brattebø (Nov. 2016). "Dynamic Building Stock Modelling: Application to 11 European Countries to Support the Energy Efficiency and Retrofit Ambitions of the EU". In: *Energy and Buildings* 132, pp. 26–38. ISSN: 03787788. DOI: 10.1016/j.enbuild.2016.05.100. (Visited on 03/05/2025).

Textile Exchange (2026). *Materials Market Reports 2017-2025*. en-US. URL: https://textileexchange.org/knowledge-center/reports/ (visited on 07/24/2026).

U.S. Geological Survey, National Minerals Information Center (2024). *Cement - Historical Statistics (Data Series 140)*. en. URL: https://www.usgs.gov/media/files/cement-historical-statistics-data-series-140.

Uekert, Taylor, Avantika Singh, Jason S. DesVeaux, Tapajyoti Ghosh, Arpit Bhatt, Geetanjali Yadav, Shaik Afzal, Julien Walzberg, Katrina M. Knauer, Scott R. Nicholson, Gregg T. Beckham, and Alberta C. Carpenter (Jan. 23, 2023). "Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics". In: *ACS Sustainable Chemistry & Engineering* 11.3. Publisher: American Chemical Society, pp. 965–978. DOI: 10.1021/acssuschemeng.2c05497. URL: https://doi.org/10.1021/acssuschemeng.2c05497 (visited on 06/26/2025).

UNCTAD (2025a). *Classifications | UNCTAD Data Hub*. URL: https://unctadstat.unctad.org/EN/Classifications.html#PLASTICS_PRODUCTS (visited on 12/18/2025).

— (2025b). *Plastics trade by partner, annual (analytical)*. URL: https://unctadstat.unctad.org/datacentre/reportInfo/US.PlasticsTradebyPartner (visited on 10/23/2025).

UNEP (Dec. 2020). *National Guidance for Plastic Pollution Hotspotting and Shaping Action*. URL: https://plastichotspotting.lifecycleinitiative.org/ (visited on 12/23/2025).

United Nations, Department on Economic and Social Affairs, Population Division (2022). *World Population Prospects 2022*. URL: https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022.

US EPA, OLEM (Sept. 2017). *Plastics: Material-Specific Data*. en. Collections and Lists. URL: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data (visited on 10/23/2025).

Wiedenhofer, Dominik, André Baumgart, Sarah Matej, Doris Virág, Gerald Kalt, Maud Lanau, Danielle Densley Tingley, Zhiwei Liu, Jing Guo, Hiroki Tanikawa, and Helmut Haberl (Jan. 2024). "Mapping and Modelling Global Mobility Infrastructure Stocks, Material Flows and Their Embodied Greenhouse Gas Emissions". In: *Journal of Cleaner Production* 434, p. 139742. ISSN: 09596526. DOI: 10.1016/j.jclepro.2023.139742. (Visited on 03/04/2025).

World Bank (2023a). *Population Estimates and Projections by the World Bank 1960-2050*.
— (2023b). *Select indicators from the World Development Indicators database from the World Bank*.
World Steel Association (May 2021). *Scrap Use in the Steel Industry. Fact Sheet*. Brussels, Belgium. URL: https://worldsteel.org/wp-content/uploads/Fact-sheet-on-scrap_2021.pdf (visited on 12/18/2025).
— (2023a). *Steel Statistical Yearbook*. Annual publication 1978–2023. Brussels, Belgium: World Steel Association AISBL. URL: https://worldsteel.org/media/publications/ (visited on 12/18/2025).
— (2023b). *Steel Statistical Yearbook 2023*. World Steel Association AISBL. URL: https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2023.pdf (visited on 12/18/2025).
— (Nov. 2025a). *Raw materials*. [Online; accessed 18. Dec. 2025]. Brussels, Belgium. URL: https://worldsteel.org/other-topics/raw-materials.
— (2025b). *World Steel in Figures*. Annual publication 2002–2025. Brussels, Belgium: World Steel Association AISBL. URL: https://worldsteel.org/media/publications/ (visited on 12/18/2025).
Xi, Fengming, Steven J. Davis, Philippe Ciais, Douglas Crawford-Brown, Dabo Guan, Claus Pade, Tiemao Shi, Mark Syddall, Jie Lv, Lanzhu Ji, Longfei Bing, Jiaoyue Wang, Wei Wei, Keun-Hyeok Yang, Björn Lagerblad, Isabel Galan, Carmen Andrade, Ying Zhang, and Zhu Liu (Nov. 2016). "Substantial global carbon uptake by cement carbonation". In: *Nature Geoscience* 9.12, pp. 880–883. ISSN: 1752-0908. DOI: 10.1038/ngeo2840. URL: http://dx.doi.org/10.1038/ngeo2840.
Yadav, Geetanjali, Avantika Singh, Abhijit Dutta, Taylor Uekert, Jason S. DesVeaux, Scott R. Nicholson, Eric C.D. Tan, Calvin Mukarakate, Joshua A. Schaidle, Cody J. Wrasman, Alberta C. Carpenter, Robert M. Baldwin, Yuriy Román-Leshkov, and Gregg T. Beckham (2023). "Techno-economic analysis and life cycle assessment for catalytic fast pyrolysis of mixed plastic waste". en. In: *Energy & Environmental Science* 16.9. Publisher: Royal Society of Chemistry, pp. 3638–3653. DOI: 10.1039/D3EE00749A. URL: https://pubs.rsc.org/en/content/articlelanding/2023/ee/d3ee00749a (visited on 07/07/2025).
Yonggang, Wang, Man Juan, Ni Yao, Gao Yang, and Chen Yan (July 2024). *Plastic Production, Consumption, Discarding, and Recycling Across China and Across the World*. URL: http://www.gefsgp.cn/detail.php?id=717&fid=13&cid=3 (visited on 10/23/2025).

S3 Additional Figures

This section shows the results figures of the main paper (Section 4) for all materials, and additionally in the REMIND 12-region aggregation it was computed with: the regional comparison (Figure 5, Subsection S3.1), the Sankey diagrams (Figure 6, Subsection S3.3), trade (Figure 7, Subsection S3.4), and the scenario comparison (Figure 8, Subsection S3.5). The figures from the main paper are repeated here for completeness and side-by-side comparison. The exogenous model inputs GDP per capita and population are shown in Subsections S3.6 and S3.7. Unless stated otherwise, all results refer to the SSP2 scenario, computed on REMIND 12-region resolution.

The MFA can be computed with arbitrary regional aggregation, and demand trajectories are provided with the REMIND 12-region aggregation (h12) and with country level (iso249) resolution. The resolution of the MFA computation can have an effect on the results, even if the results are aggregated to the same regional aggregation after the computation. For details on these effects, see the README in the data repository. Two subsections illustrate the effect of different regional aggregations on the results: Subsection S3.2 shows the results of Figure 5 for a model run with the MFA computed on country level, and aggregated to the respective regions after the computation. Subsection S3.8 directly compares production and per-capita in-use stocks for both resolutions, with one panel per region.

In all time series plots, the dashed vertical line marks the last historical year of the respective material.

S3.1 Figure 5 - Regional comparison

Each column refers to one material. The rows show per-capita in-use stocks, per-capita production, and total production by region. The dotted black line shows the global value (global average for per-capita values, global total for production).

S3.1.1 REMIND 12-region aggregation

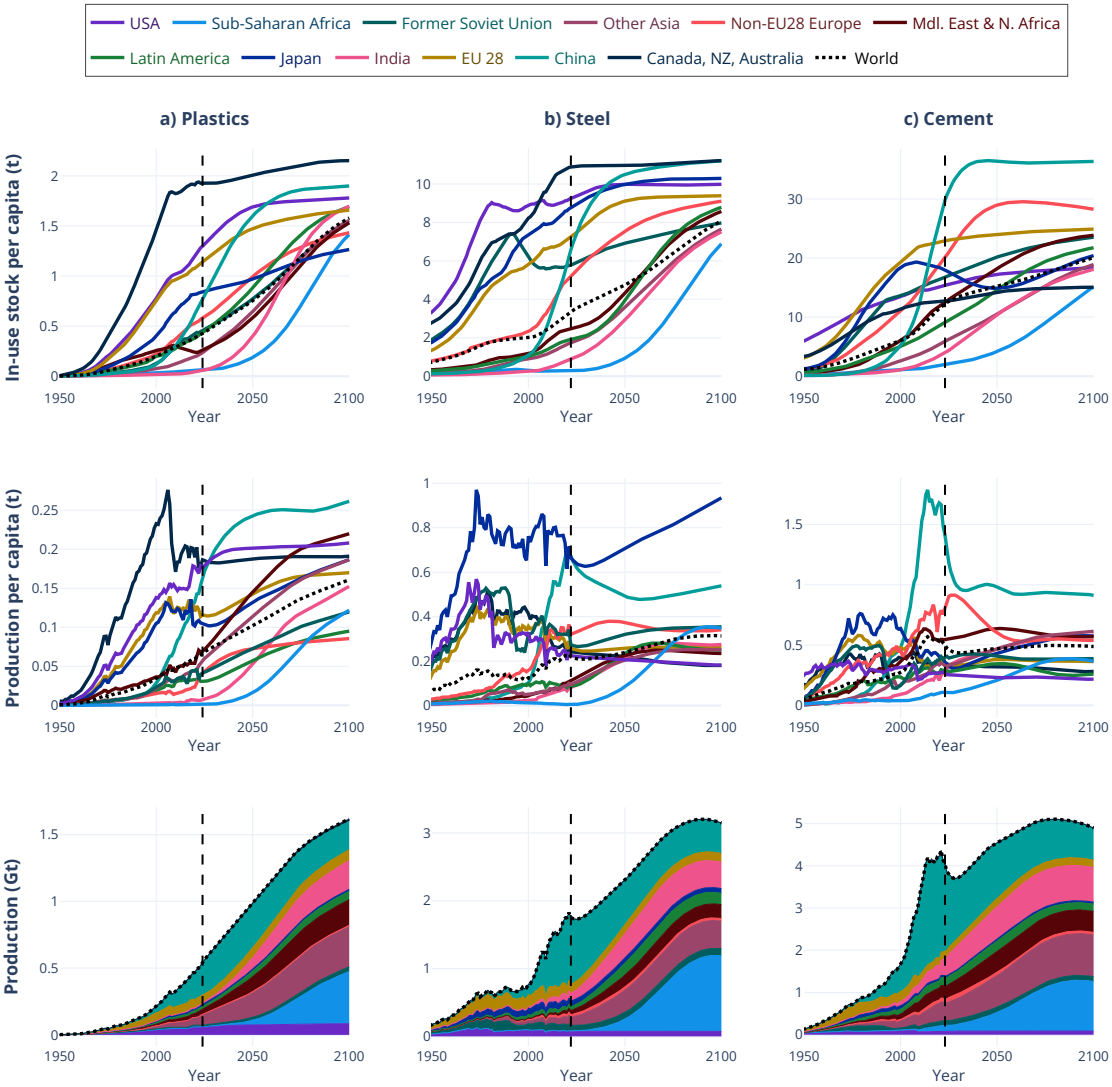


Figure S5: Paper Figure 5 for the **REMIND 12-region aggregation**: per-capita in-use stocks (top), per-capita production (middle), and production stacked by region (bottom) for plastics, steel, and cement.

S3.1.2 Results section 5-region aggregation

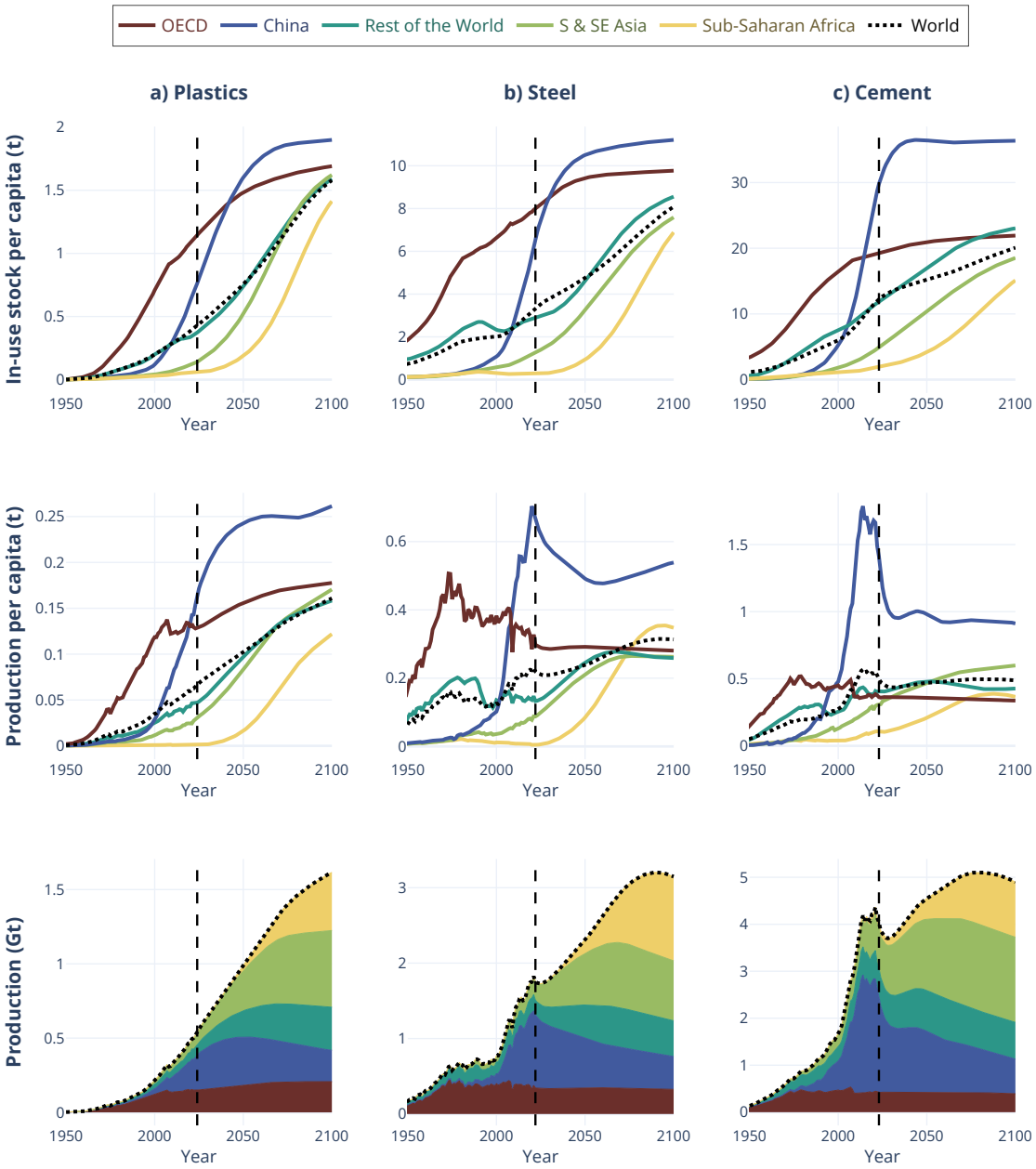


Figure S6: Paper Figure 5 for the results section **5-region aggregation**: per-capita in-use stocks (top), per-capita production (middle), and production stacked by region (bottom) for plastics, steel, and cement.

S3.2 Figure 5 - Regional comparison - MFA computed with country-resolution

Same as the previous subsection, but with the MFA computed on country level (see the introduction of Section S3 for details).

The results are aggregated to the respective regions after the computation.

S3.2.1 REMIND 12-region aggregation

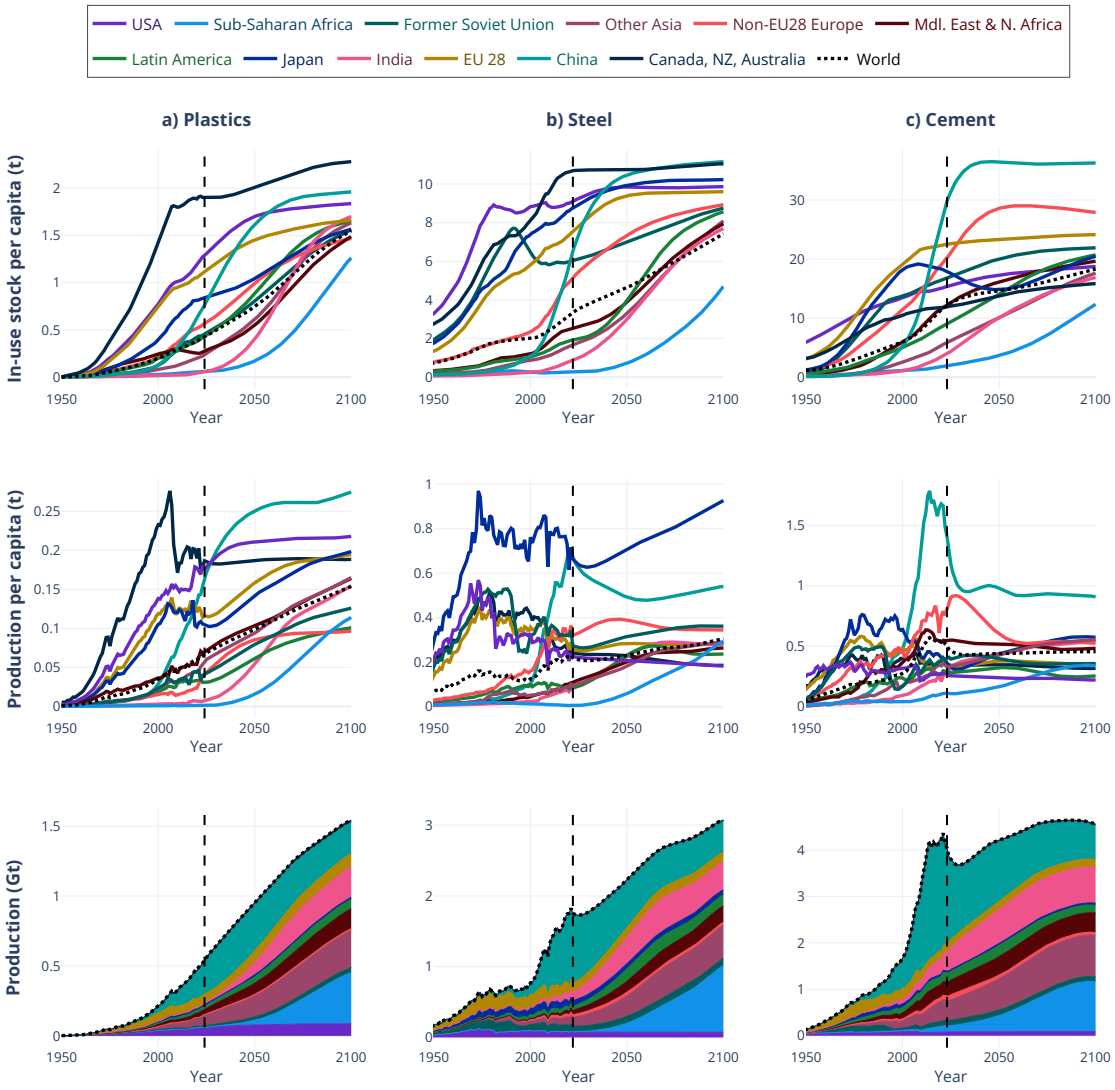


Figure S7: Paper Figure 5 for the **REMIND 12-region aggregation**; MFA computed with **country-resolution**.

S3.2.2 Results section 5-region aggregation

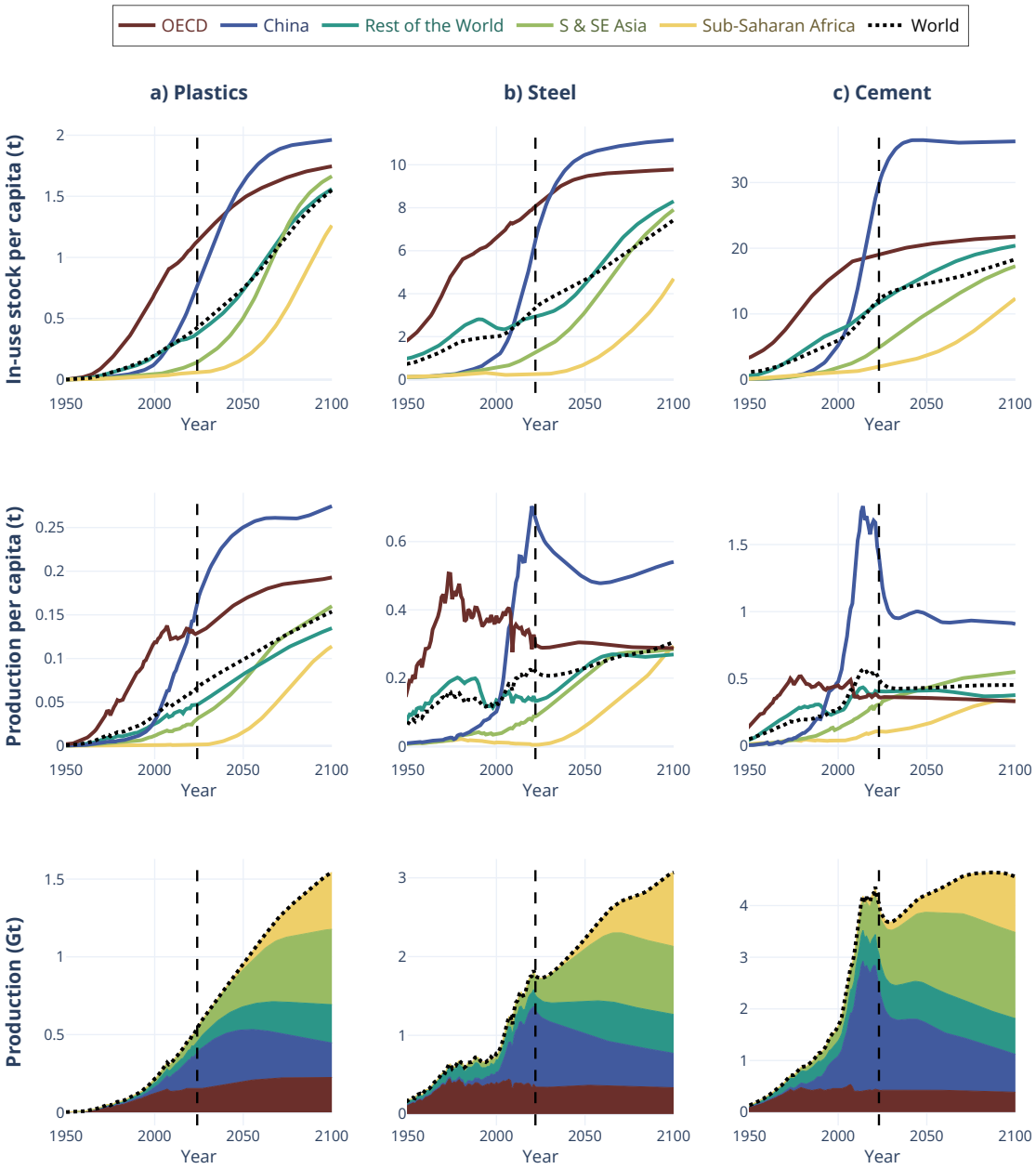


Figure S8: Paper Figure 5 for the results section **5-region aggregation**; MFA computed with **country-resolution**.

S3.3 Figure 6 - Sankey diagrams

Global material flows in the year 2050. Imports, exports, and flows from and to the system environment are not shown.

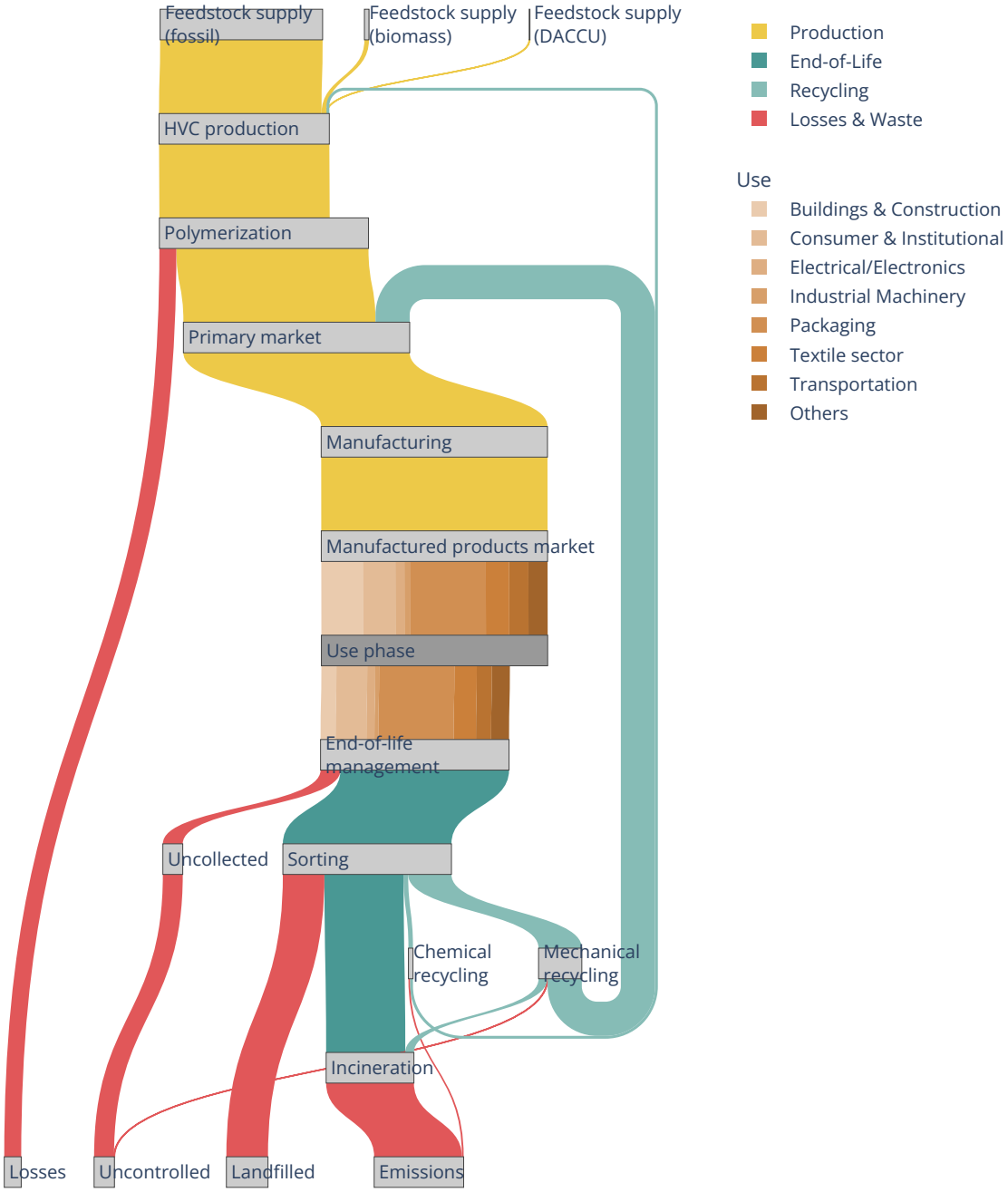


Figure S9: Paper Figure 6 for **plastics**: global plastics flows in 2050. Contrary to the main paper, also non-carbon mass flows are included, and the atmospheric stock/cycle is omitted.

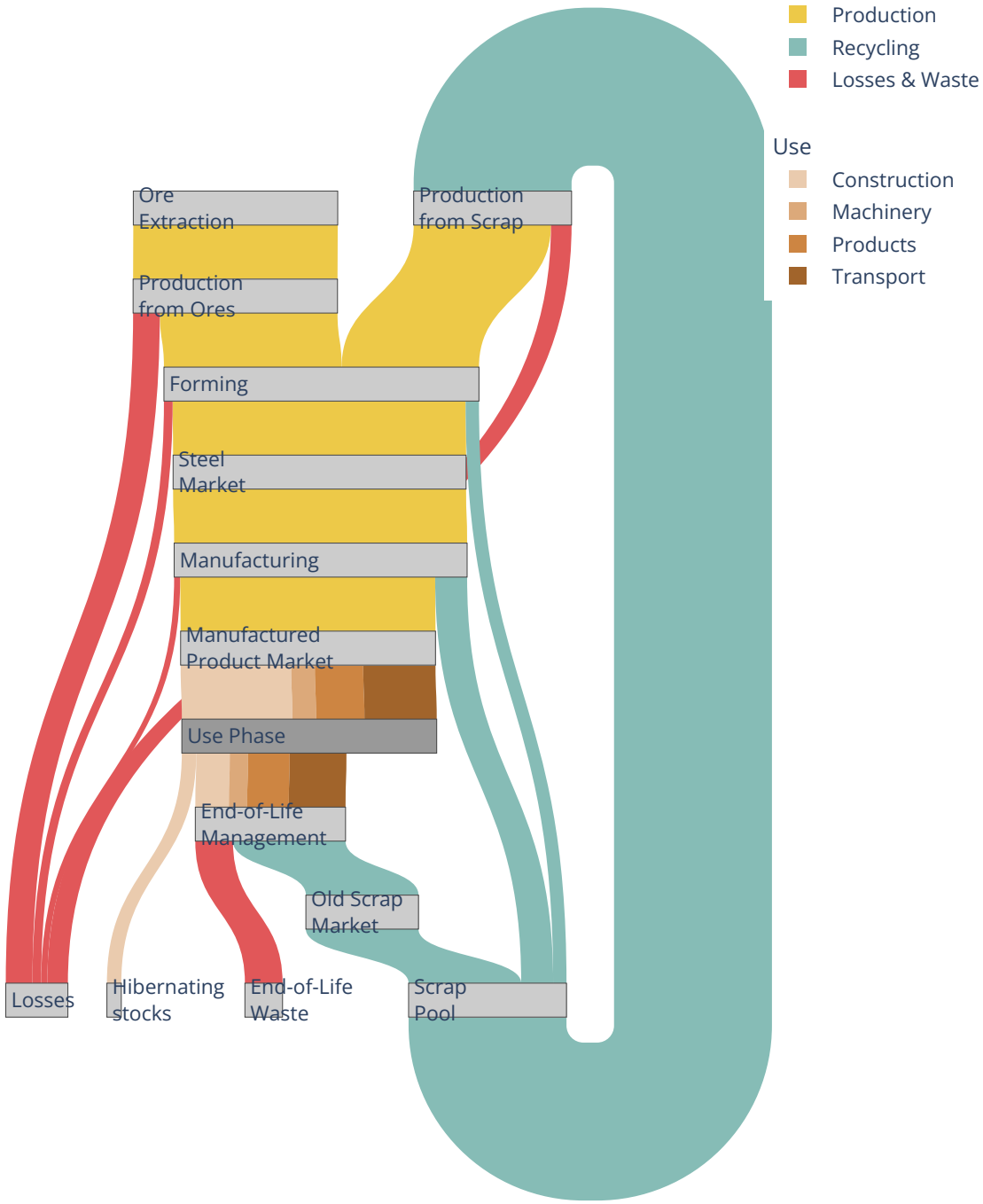


Figure S10: Paper Figure 6 for **steel**: global steel flows in 2050.

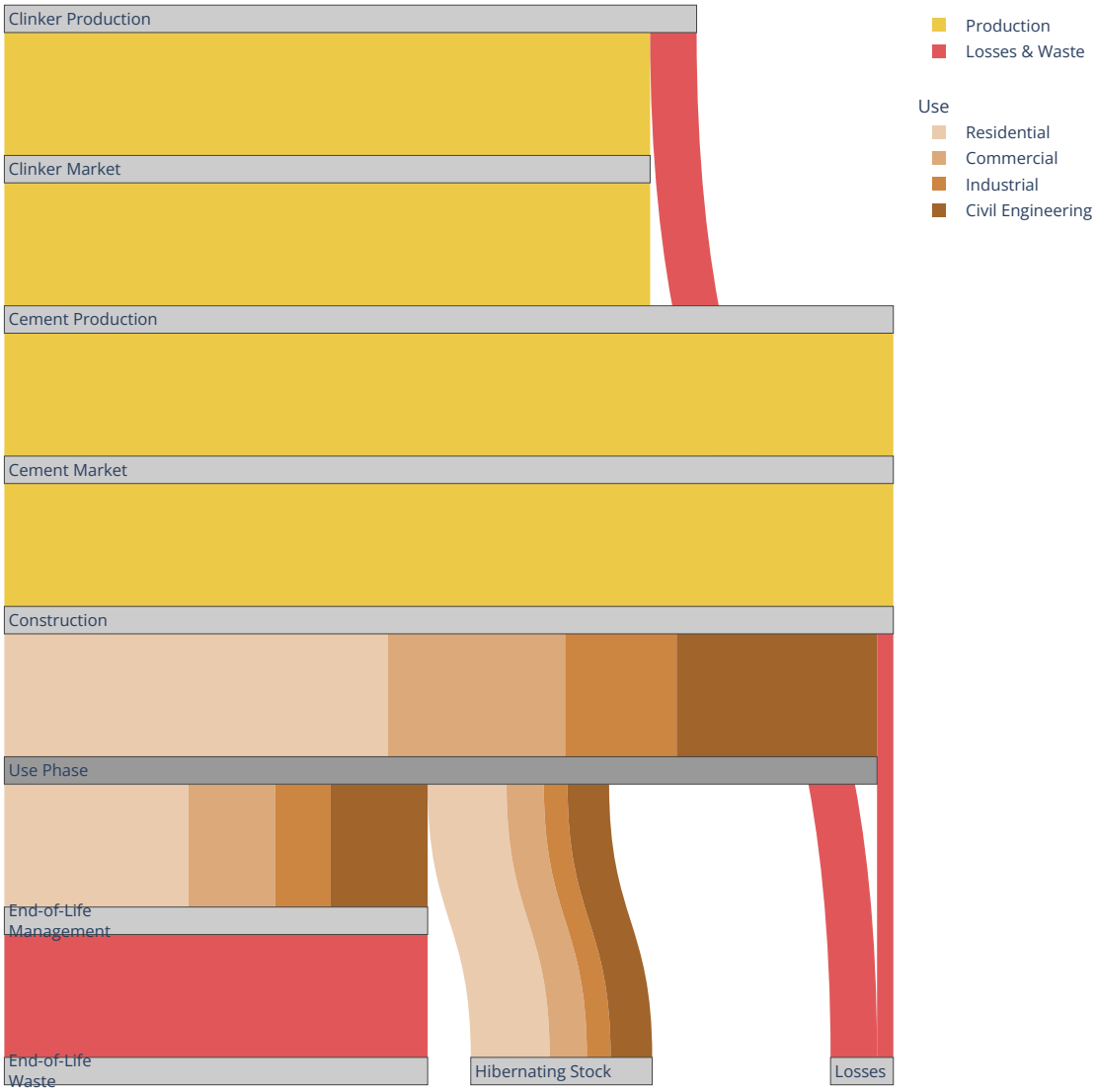


Figure S11: Paper Figure 6 for **cement**: global cement flows in 2050.

S3.4 Figure 7 - Trade

Each figure shows exports (top left), imports (bottom left), export share (top right), and import share (bottom right) by region. The export share is defined relative to regional production, the import share relative to regional demand. Imports and import shares are plotted on reversed vertical axes.

S3.4.1 REMIND 12-region aggregation

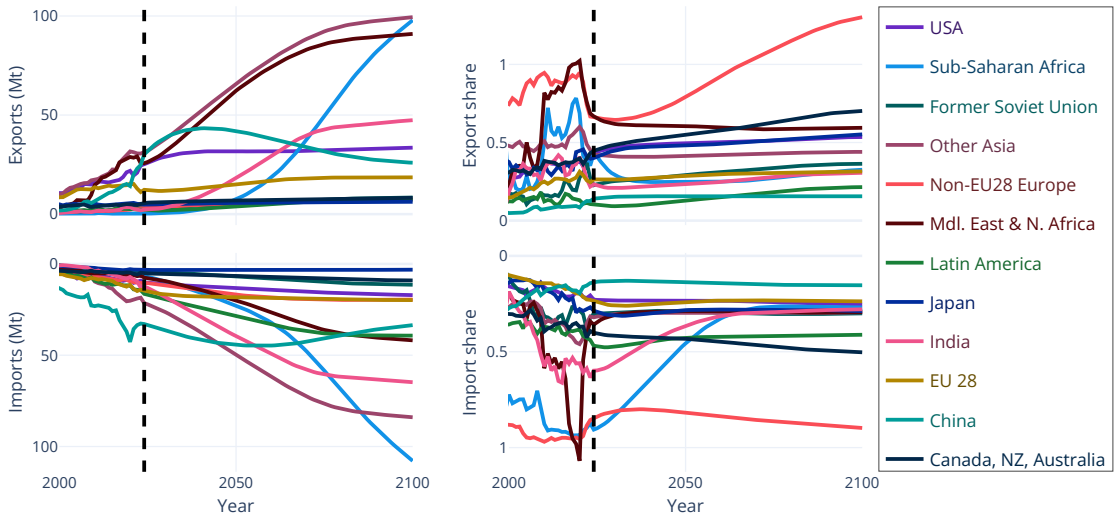


Figure S12: Paper Figure 7 for **plastics** in the **REMIND 12-region aggregation**: exports, imports, and the respective shares in production and demand.

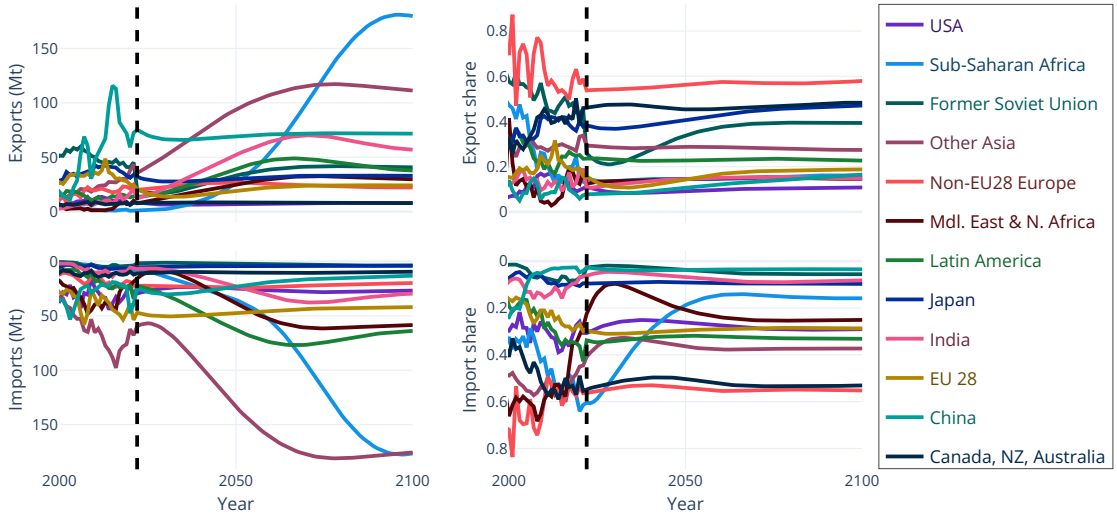


Figure S13: Paper Figure 7 for **steel** in the **REMIND 12-region aggregation**: exports, imports, and the respective shares in production and demand.

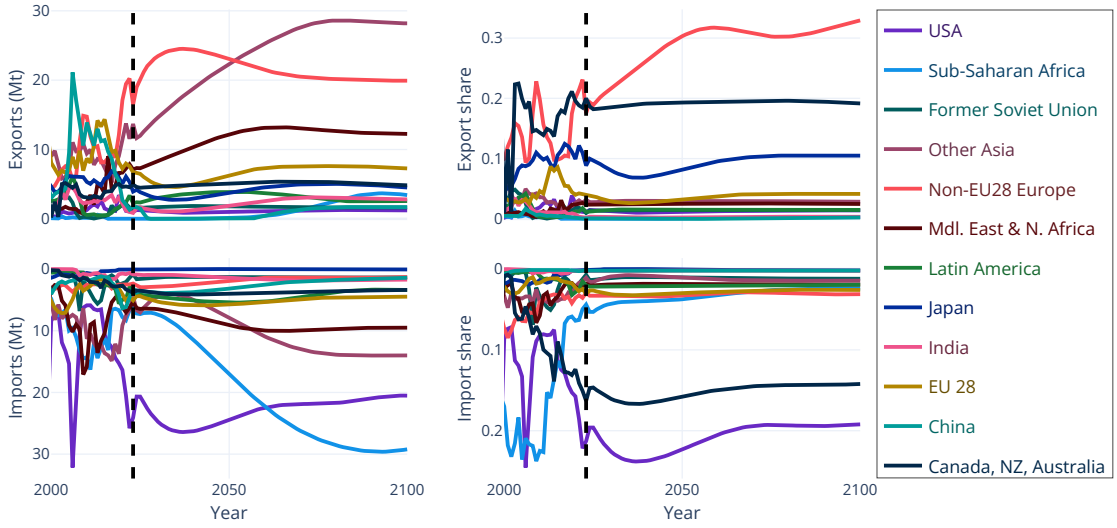


Figure S14: Paper Figure 7 for **cement** in the **REMIND 12-region aggregation**: exports, imports, and the respective shares in production and demand.

S3.4.2 Results section 5-region aggregation

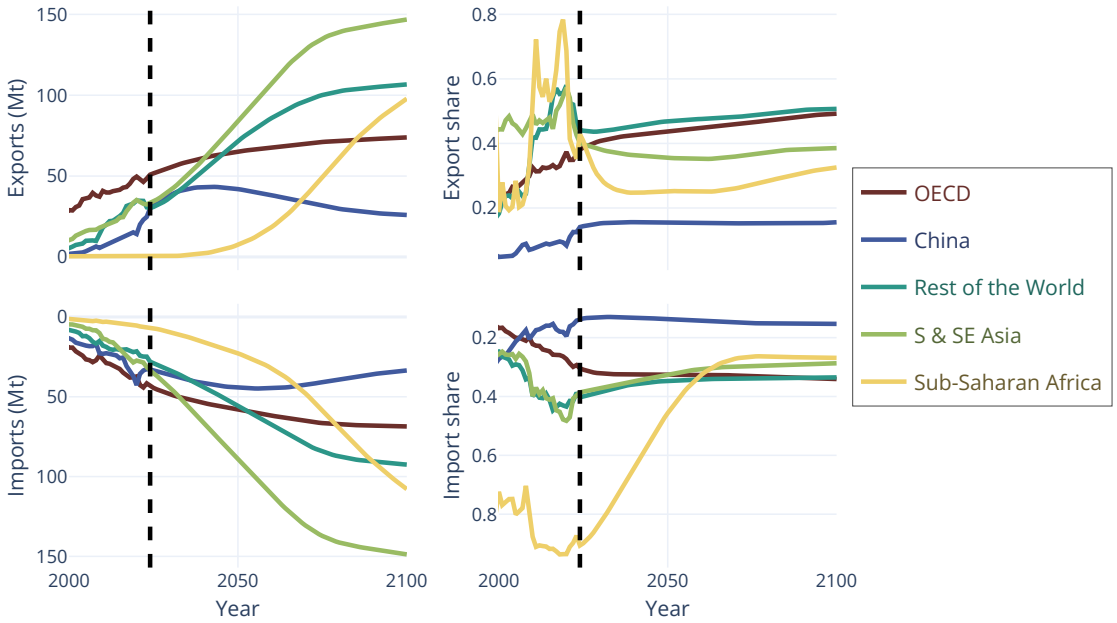


Figure S15: Paper Figure 7 for **plastics** in the results section **5-region aggregation**: exports, imports, and the respective shares in production and demand.

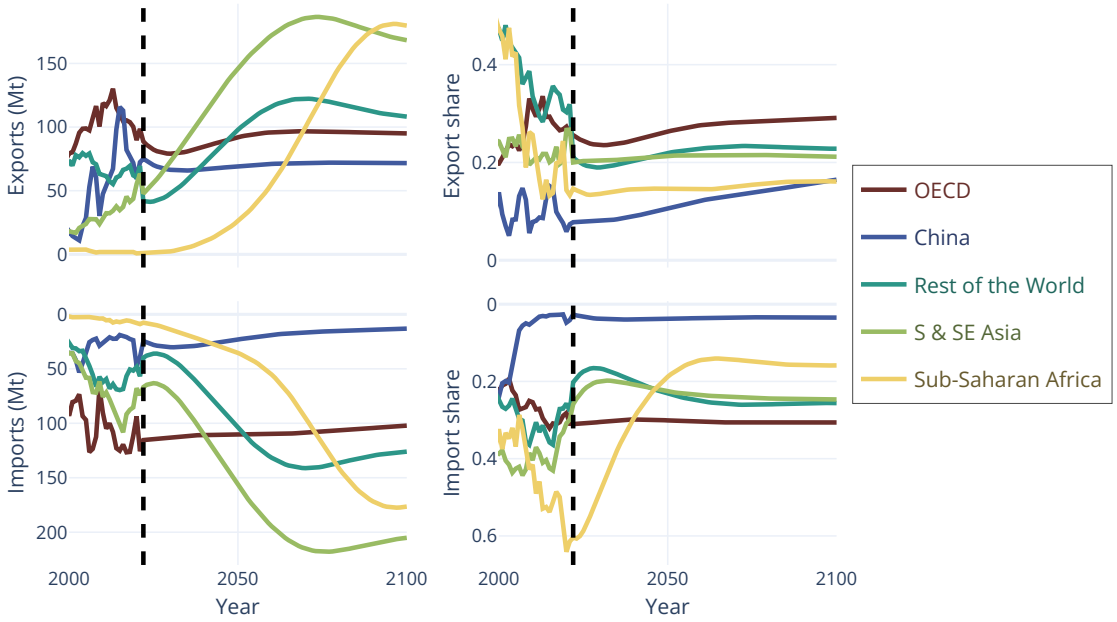


Figure S16: Paper Figure 7 for **steel** in the results section **5-region aggregation**: exports, imports, and the respective shares in production and demand.

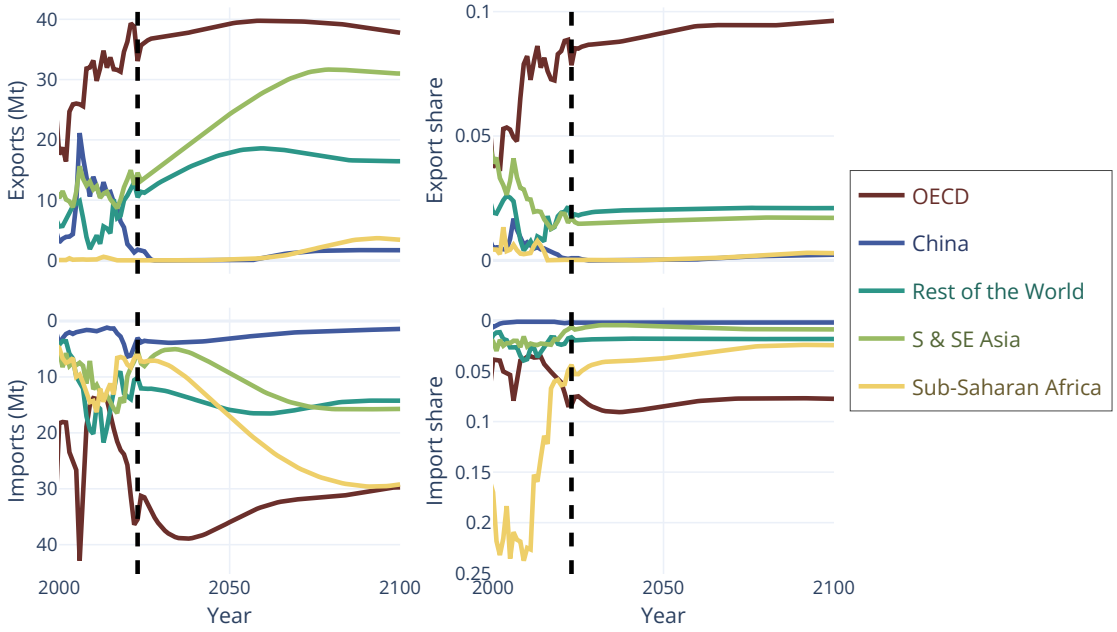


Figure S17: Paper Figure 7 for **cement** in the results section **5-region aggregation**: exports, imports, and the respective shares in production and demand.

S3.5 Figure 8 - Scenario comparison

Each figure shows production in the scenarios SSP2, SSP1-drivers, and SSP1-CE. The framed panel shows the global total, the other panels show individual regions.

S3.5.1 REMIND 12-region aggregation

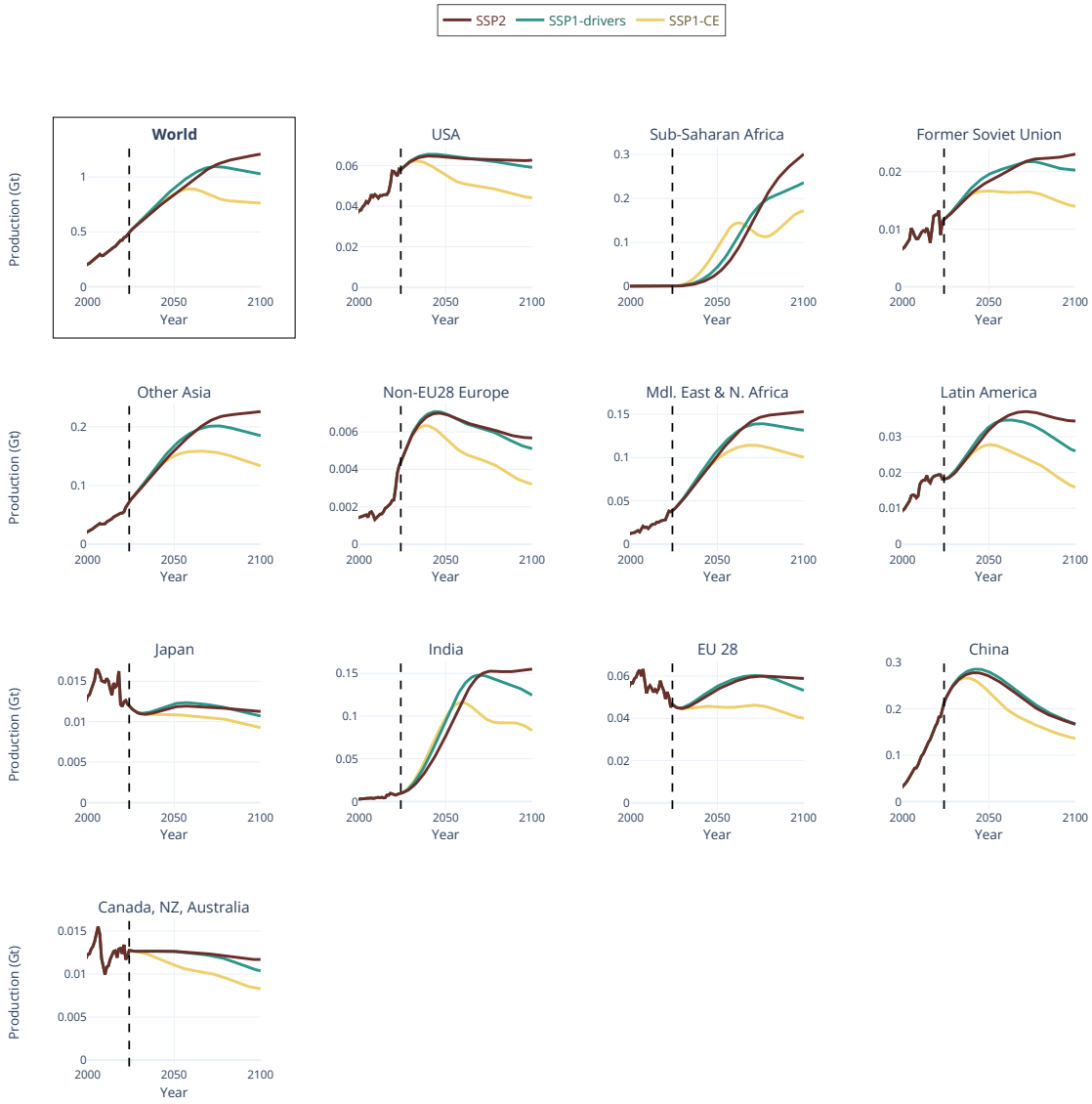


Figure S18: Paper Figure 8 for **plastics** in the **REMIND 12-region aggregation**: production by scenario, globally and per region.

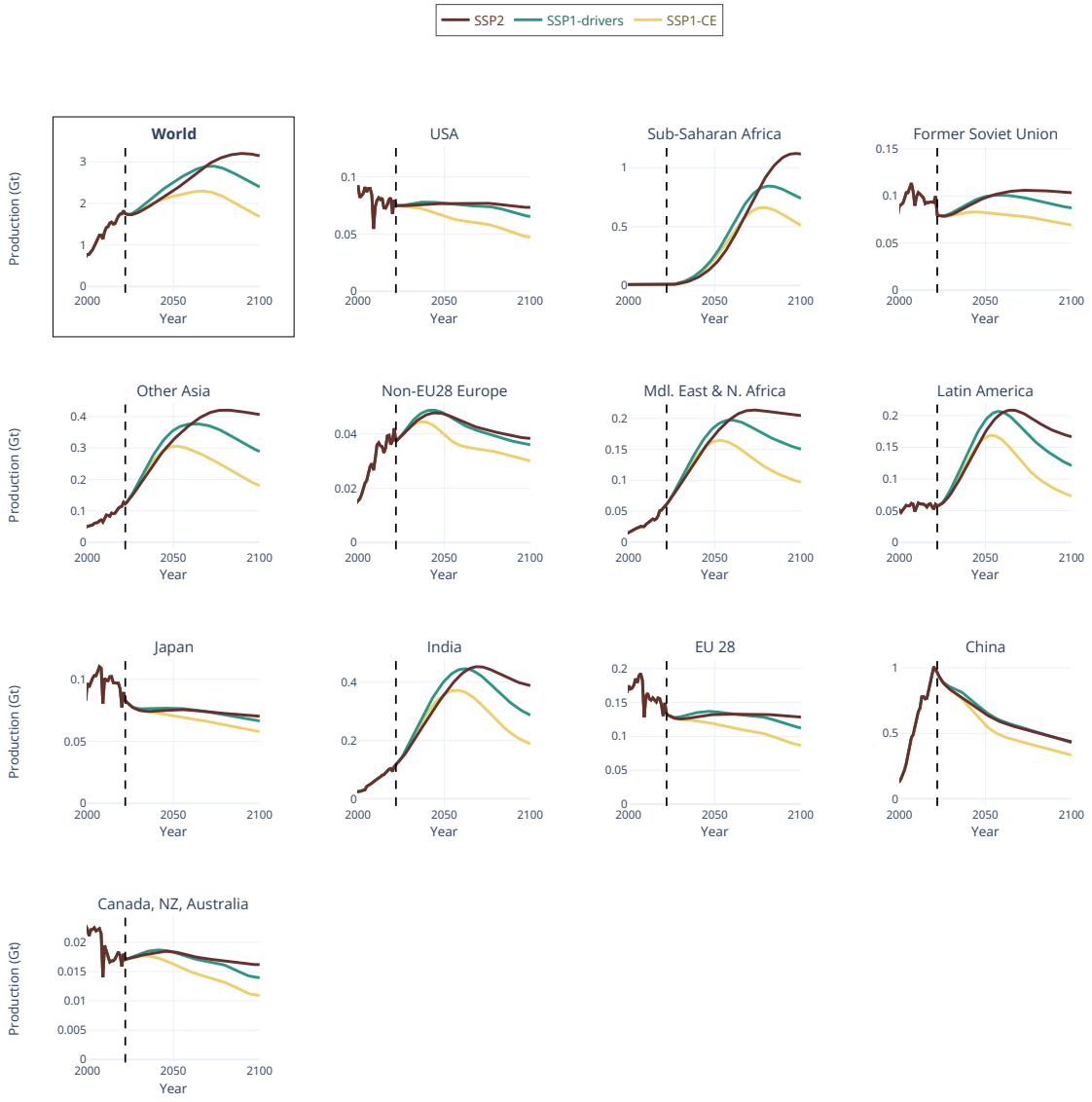


Figure S19: Paper Figure 8 for **steel** in the **REMIND 12-region aggregation**: production by scenario, globally and per region.

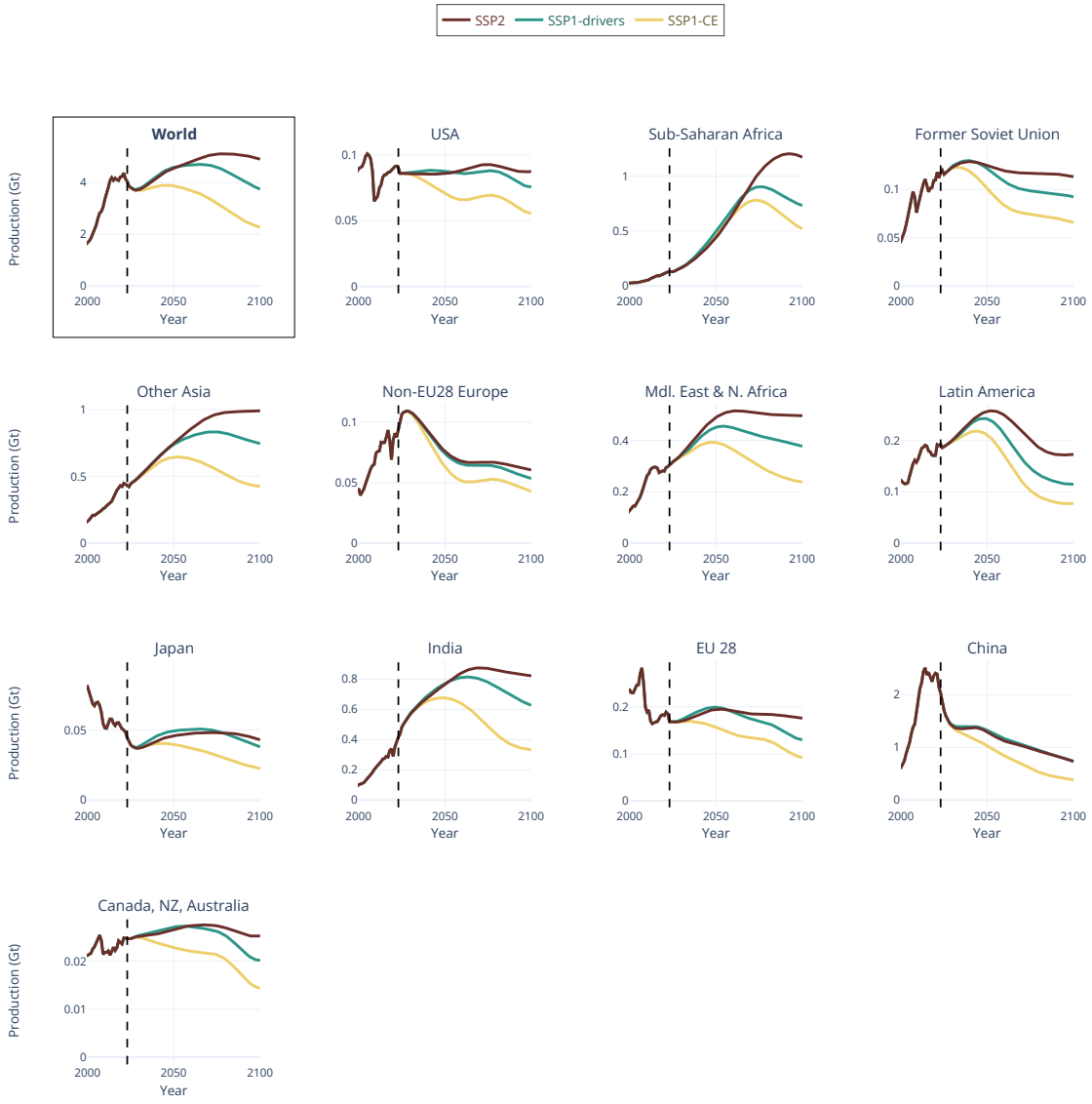


Figure S20: Paper Figure 8 for **cement** in the **REMIND 12-region aggregation**: production by scenario, globally and per region.

S3.5.2 Results section 5-region aggregation



Figure S21: Paper Figure 8 for **plastics** in the results section **5-region aggregation**: production by scenario, globally and per region.



Figure S22: Paper Figure 8 for **steel** in the results section **5-region aggregation**: production by scenario, globally and per region.

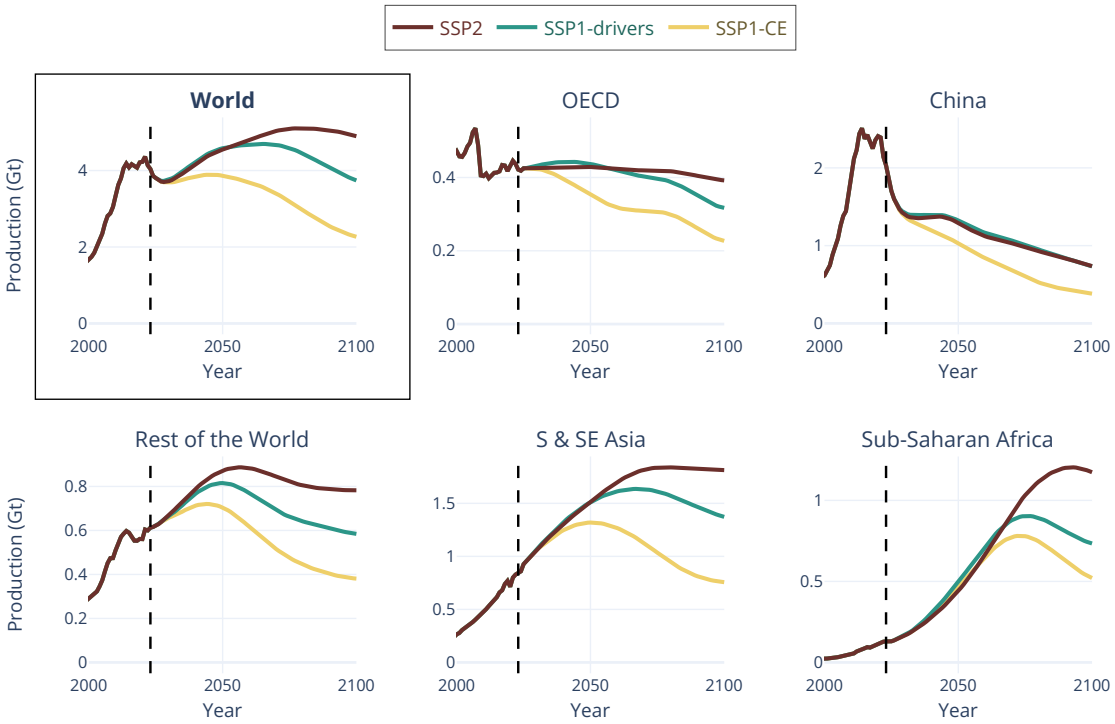


Figure S23: Paper Figure 8 for **cement** in the results section **5-region aggregation**: production by scenario, globally and per region.

S3.6 GDP per capita (SSP2)

GDP per capita is an exogenous model input and serves as predictor in the extrapolation of in-use stocks.

S3.6.1 REMIND 12-region aggregation

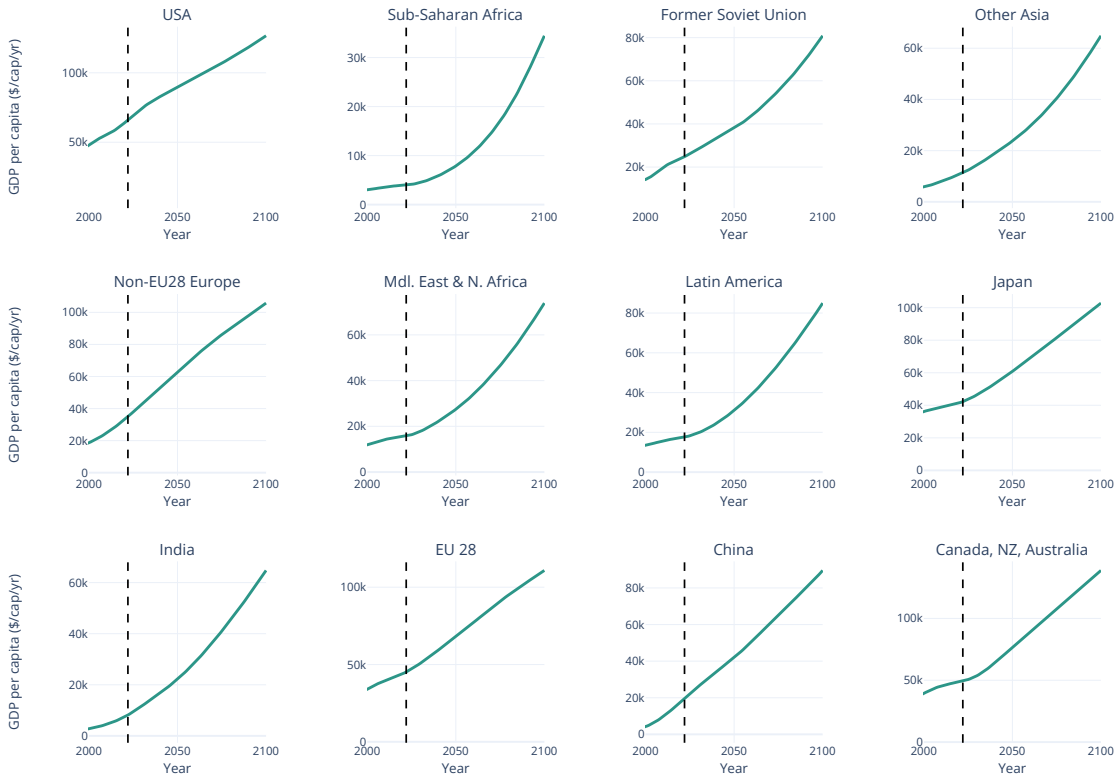


Figure S24: GDP per capita (SSP2) per region of the **REMIND 12-region aggregation**.

S3.6.2 Results section 5-region aggregation



Figure S25: GDP per capita (SSP2) per region of the results section **5-region aggregation**.

S3.7 Population (SSP2)

Population is an exogenous model input and converts per-capita in-use stocks to total in-use stocks.

S3.7.1 REMIND 12-region aggregation

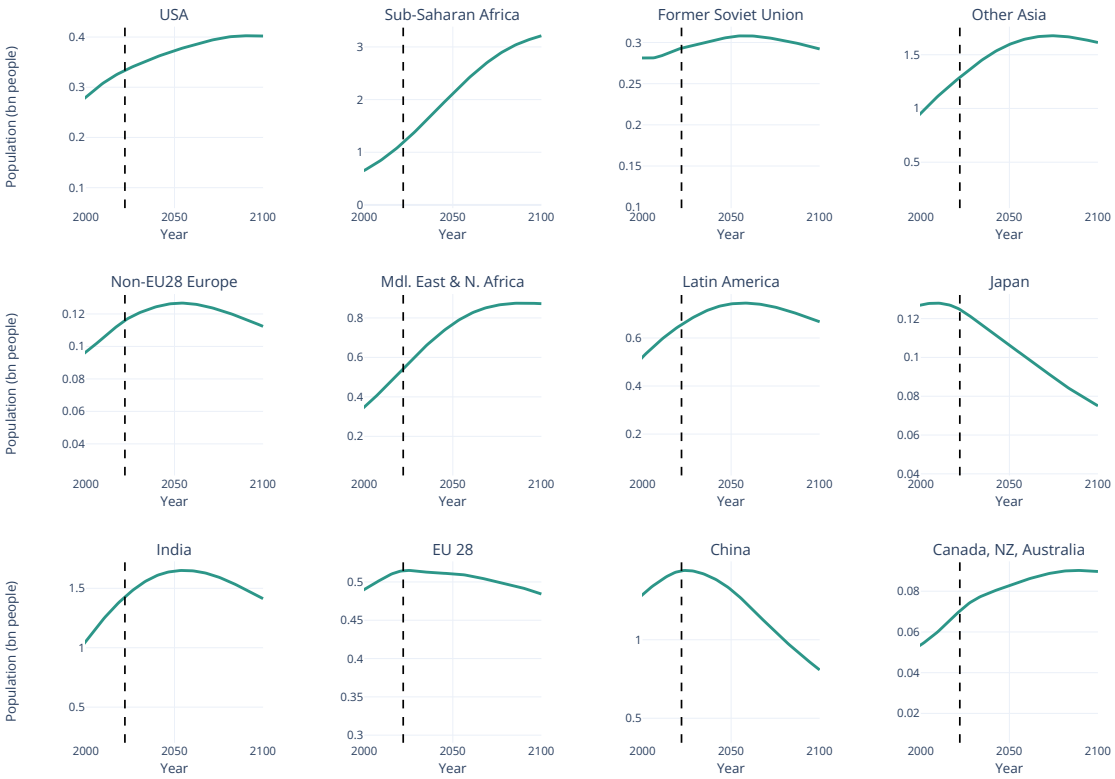


Figure S26: Population (SSP2) per region of the **REMIND 12-region aggregation**.

S3.7.2 Results section 5-region aggregation



Figure S27: Population (SSP2) per region of the results section **5-region aggregation**.

S3.8 Comparison of REMIND 12-region and country-level resolution

The MFA can be computed either on the REMIND 12-region aggregation (h12) or on country level (iso249). Results computed on country level are aggregated to the REMIND 12 regions after the computation (iso249 → h12).

See the introduction of Section S3 for details.

S3.8.1 Production

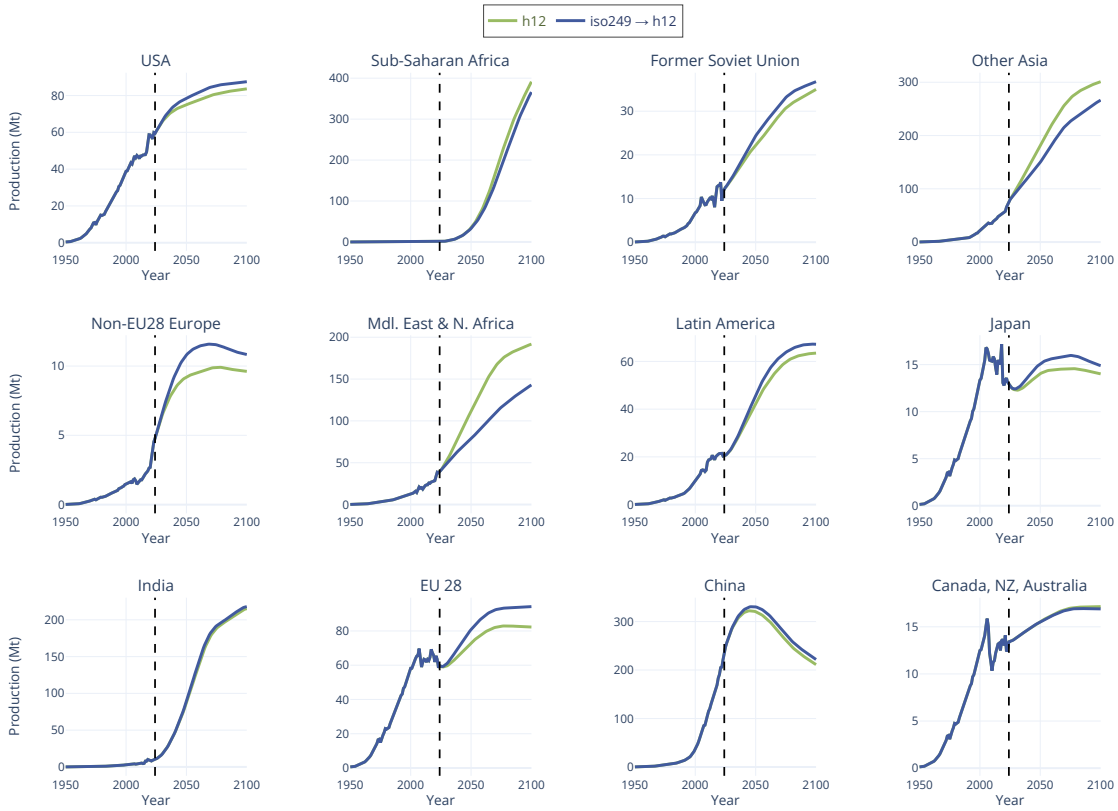


Figure S28: **Plastics** production per REMIND region, computed on REMIND 12-region resolution (h12) and on country-level resolution aggregated to REMIND regions (iso249 → h12).

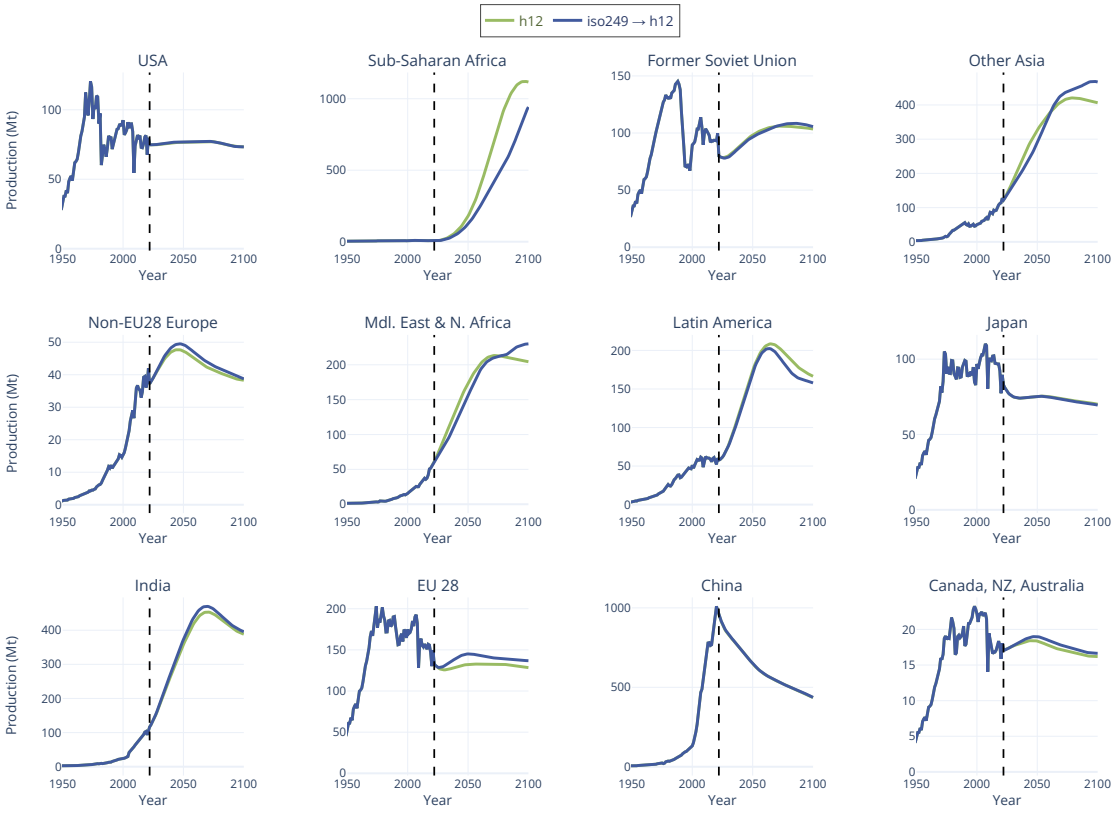


Figure S29: **Steel** production per REMIND region, computed on REMIND 12-region resolution (h12) and on country-level resolution aggregated to REMIND regions (iso249 → h12).

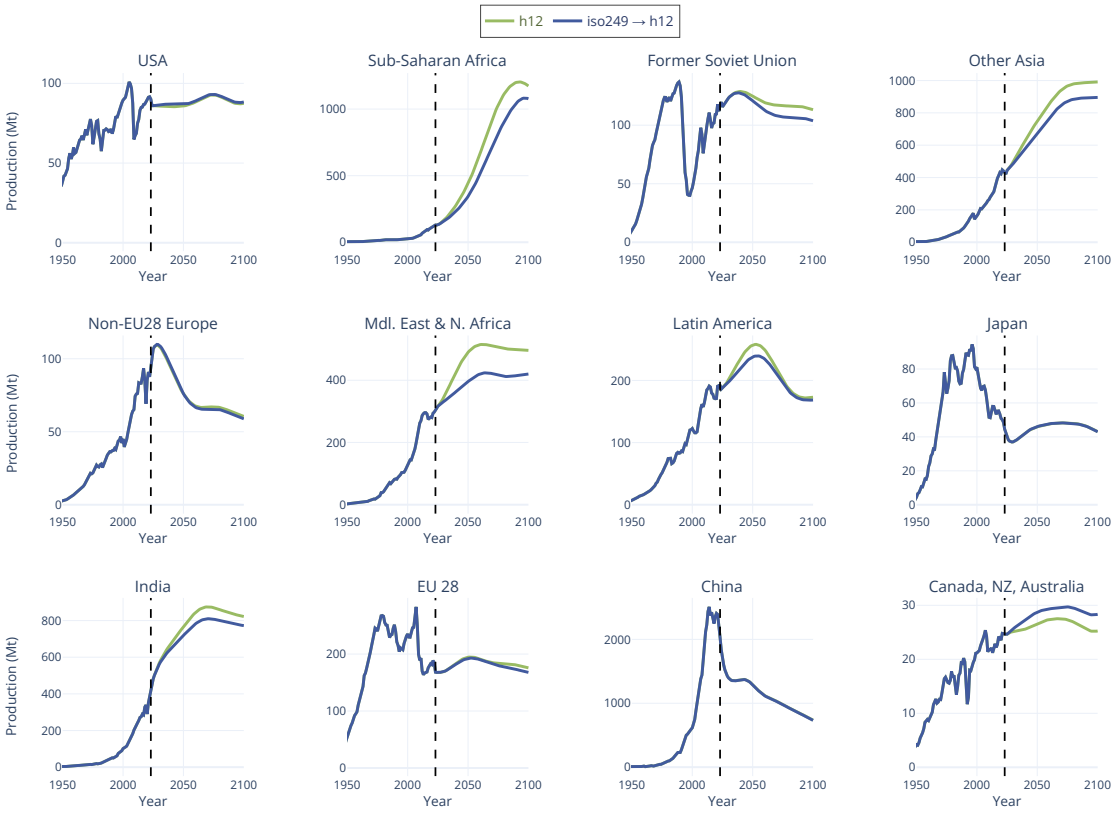


Figure S30: **Cement** production per REMIND region, computed on REMIND 12-region resolution (h12) and on country-level resolution aggregated to REMIND regions (iso249 → h12).

S3.8.2 Per-capita in-use stocks

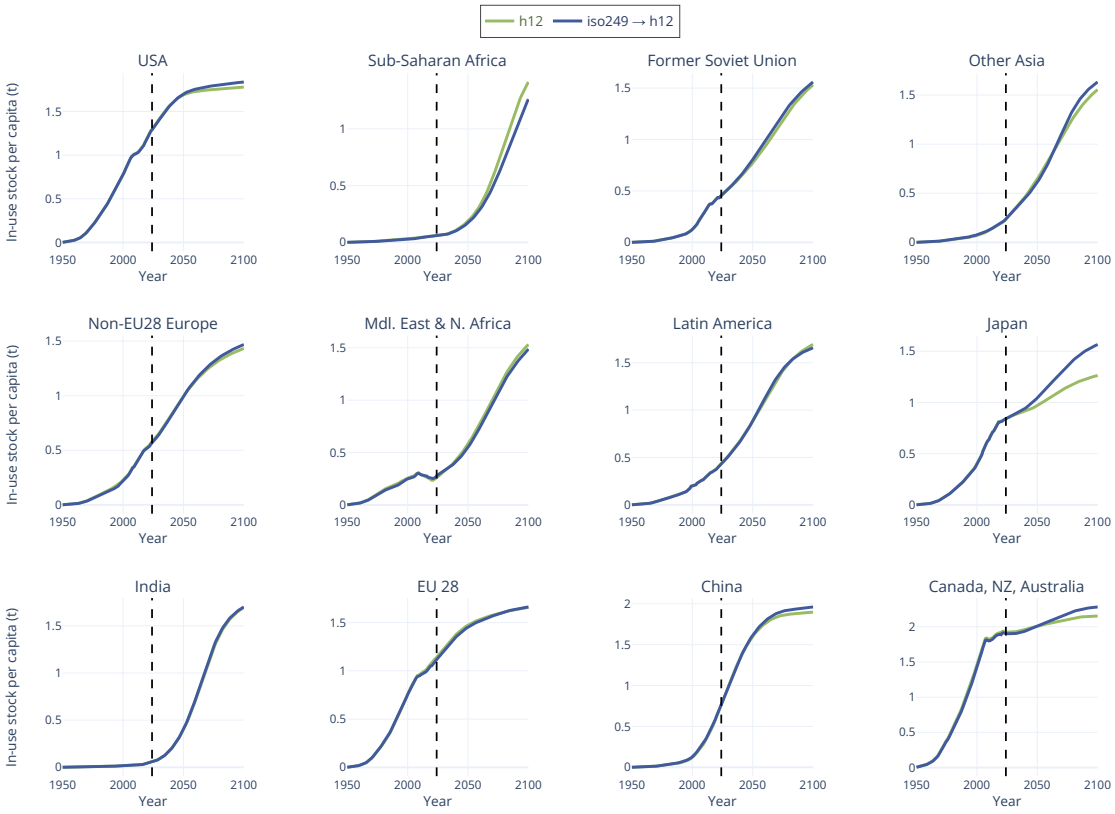


Figure S31: Per-capita in-use stocks of **plastics** per REMIND region, computed on REMIND 12-region resolution (h12) and on country-level resolution aggregated to REMIND regions (iso249 → h12).

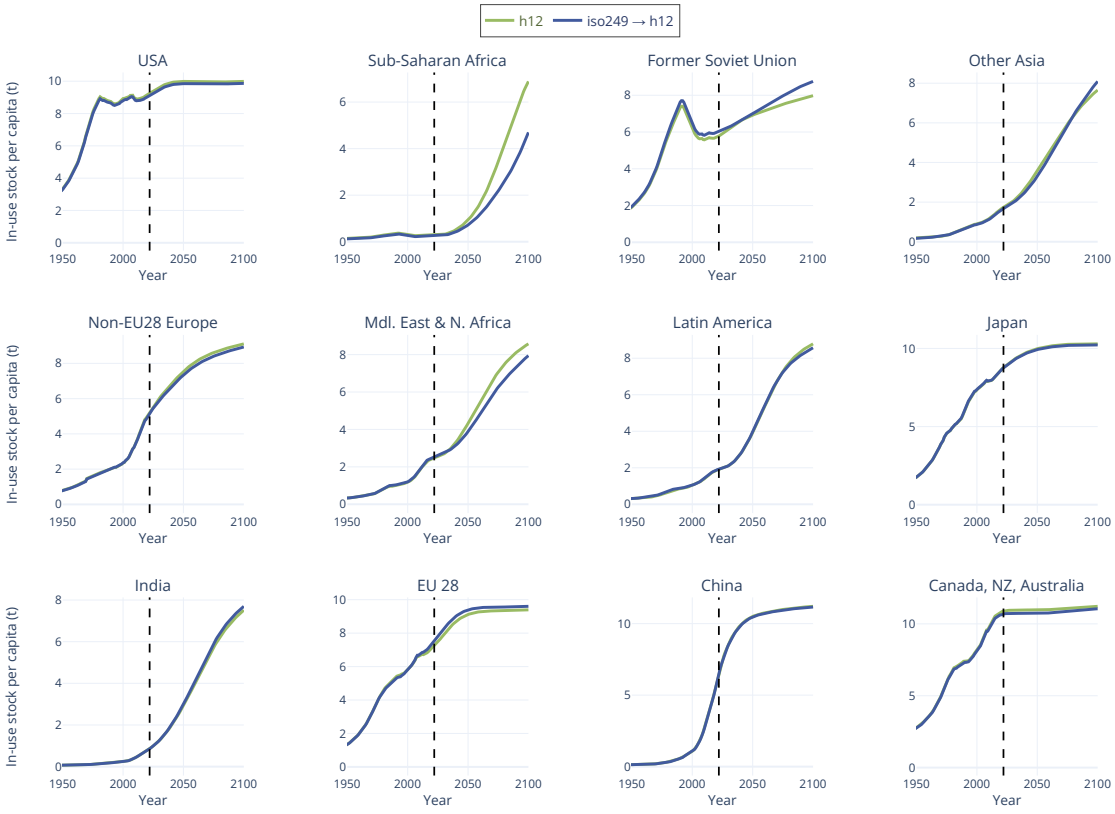


Figure S32: Per-capita in-use stocks of **steel** per REMIND region, computed on REMIND 12-region resolution (h12) and on country-level resolution aggregated to REMIND regions (iso249 → h12).

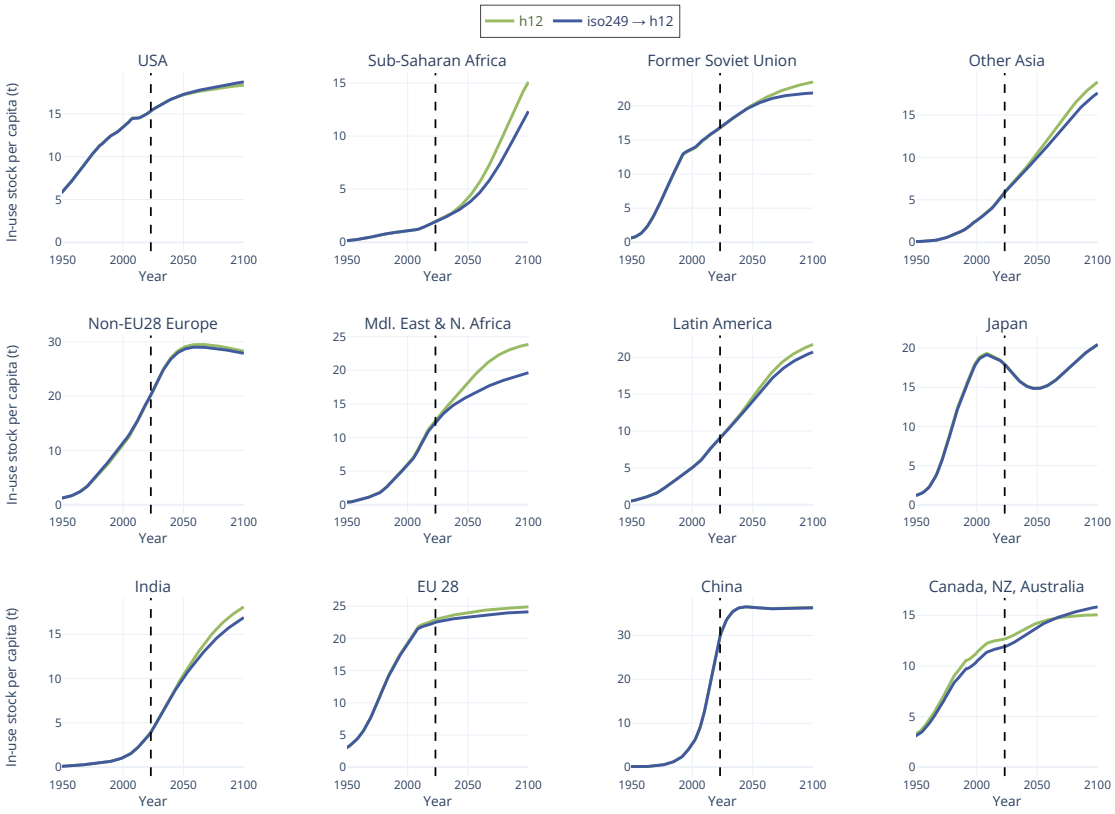


Figure S33: Per-capita in-use stocks of **cement** per REMIND region, computed on REMIND 12-region resolution (h12) and on country-level resolution aggregated to REMIND regions (iso249 → h12).