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Method Article

Keywords: Material flow analysis, Circular economy, Material demand scenarios, Integrated assessment modeling

Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11566180/v1

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Additional Declarations: No competing interests reported.

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

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Abstract

Plastics, steel, and cement production are responsible for roughly one-fifth of global greenhouse gas emissions, and demand for these materials is rising rapidly. Low-emission production technologies remain costly, resource-constrained, and slow to scale. Circular economy measures are needed to reduce virgin material production. Robust demand modeling is a prerequisite for assessing both supply-side mitigation and demand-side circular economy strategies.

We present REMIND-MFA, a global, top-down, economy-wide, stock-driven, prospective material flow analysis model for plastics, steel, and cement. We publish it here as a fourfold contribution of methods, open-source code, results, and a comprehensive data set of prospective stocks and flows. To our knowledge, it is the first material flow analysis which combines all of these characteristics while covering all three materials at country-level resolution. The main methodological innovations and distinguishing contributions are: a three-step stock extrapolation algorithm that derives consistent regional demand scenarios directly from

gross domestic product and population trajectories of the shared socioeconomic pathways with minimal regional assumptions; a trade extrapolation method accounting for shifting patterns; recent historical data through at least 2022, capturing the globally significant peaks in China's steel and cement demand and the onset of their decline; and a modular, automated codebase built for coupling with models like the integrated assessment model REMIND. We show baseline and illustrative circular economy scenario results, displaying strong demand growth under current policies and the potential for circularity to reduce virgin production.

Keywords: Material flow analysis, Circular economy, Material demand scenarios, Integrated assessment modeling

Acknowledgements and Funding. We gratefully acknowledge funding from the TRANSIENCE project, grant number 01137606, funded by the European Commission within the Horizon Europe Research and Innovation Programme; from the Kopernikus-Projekt Ariadne through the German Federal Ministry of Education and Research (grant no. 03SFK5A0-2); from the PRISMA project funded by the European Commission within the Horizon Europe Research and Innovation Programme under grant agreement No. 101081604 (PRISMA); from the WinIt project funded by the German Federal Ministry for Economic Affairs and Energy (grant no. 03KSV10a); and support to Bennet Weiss by the German Academic Scholarship Foundation.

Statements and Declarations. Competing interests: The authors declare no competing interests.

Author contributions: The general model was developed by JD, BW, LS, and TD. The material models (including input data research and processing) were developed by LS and QZ (plastics), MH and JD (steel), and BW (cement). Figures were prepared by JD. The original draft of the manuscript was written by JD, with contributions from BW and LS. The manuscript was reviewed and edited by all authors. The work was supervised and funding acquired by FU and GL.

1 Introduction

The production of the basic materials plastics, steel, and cement accounts for 4.5 %, 7 %, and 7 % of global greenhouse gas emissions, respectively (Cabernard et al., 2022; IEA, 2018, 2020). Demand for these materials has more than doubled over the last three decades, with growth rates similar to or even higher than those of gross domestic product (GDP) (Kikstra et al., 2022). Alternative low-emission production technologies like green-hydrogen-based direct reduction of iron ore or carbon capture and storage in cement plants face severe problems: They are expensive (IEA, 2026; Sitra, 2019; Wu et al., 2025), they require resources with uncertain global availability that other sectors also compete for (such as biomass (Calvin et al., 2021) or carbon sequestration (Kazlou et al., 2024) potential), and have low technological maturity. Therefore, their scaling speed may be insufficient to address the climate impact of these materials (Watari et al., 2023). Moreover, materials' life cycles entail further non-climate environmental challenges that low-emission technologies do not address, including those related to resource extraction and plastic-waste pollution (UNEP & International Resource Panel, 2024). Circular economy measures therefore play a key role in reducing the virgin production of basic materials (IPCC, 2023). When policy-makers decide on the extent and concrete design of such measures, they face a number of open research questions (RQ):

RQ1: How big is the challenge? That is, what is a plausible range of future material demand trajectories in different world regions under current policies?
RQ2: What impact can circular economy measures have on virgin material production volumes? In particular, how much can material demand be reduced through measures like sufficiency or lifetime extension? How much end-of-life material is available to replace virgin production by recycling? How is this influenced by collection and recycling practices?
RQ3: How do material demand and its reduction through circularity influence feasibility of climate targets, considering limited potentials and scale-up speeds of low-emission technologies?

Material flow analysis (MFA) can address these questions when it has a long prospective time horizon, global scope, and economy-wide representation of the most emission-intensive materials: plastics, steel, and cement. Here, we present REMIND-MFA, including its methods, open-source code, results, and data. REMIND-MFA combines these capabilities in a top-down, stock-driven model. It projects future material demand (RQ1) and flows across product life-cycle stages including production, use, end-of-life, and recycling, enabling assessment of circularity measures (RQ2). Its automated, modular, and adaptable design supports both stand-alone analysis and coupling with other models, providing the basis for addressing RQ3. Most notably, it will be coupled to the REMIND integrated assessment model (Luderer et al., 2025) and integrated into the MIC3 model framework (TRANSIENCE consortium, 2026), while also supporting coupling to industrial production models or life-cycle assessment (LCA).

REMIND-MFA complements existing material-flow models in terms of scope, temporal coverage, and modeling approach. IMAGE-Materials (Arp, Daioglou, et al.,

2026; Arp, von Köckritz, et al., 2026) is a global model covering multiple materials, with demand driven by service demand in four bottom-up end-use sectors and a residual sector; steel and cement are covered economy-wide, while plastics are covered in two bottom-up sectors. MISO2 (Wiedenhofer et al., 2024) is an open, top-down, economy-wide model covering a wide range of materials, but is historical and extends only to 2016. ODYM-RECC (Pauliuk et al., 2021) is prospective but covers several basic materials only in passenger vehicles and residential buildings and for selected world regions. Material-specific prospective studies provide broader coverage for individual materials, including global steel (Pauliuk et al., 2013) and cement (Cao et al., 2020). For plastics, PLAIA (Stegmann et al., 2022) has a similar global scope and is coupled to an integrated assessment model (IAM), but does not use a stock-driven approach; Gao and Cabrera Serrenho (2025) provide a stock-driven prospective plastics MFA.

These studies incorporate the key elements of REMIND-MFA needed to address the stated RQ – global coverage, stock-driven prospective modelling, and economy-wide material cycles for plastics, steel, and cement – individually. However, to our knowledge, REMIND-MFA is the first model to combine these elements in one framework. Additional features and novelties include: a new stock projection method based on Shared Socioeconomic Pathways (SSP) (O'Neill et al., 2017) that robustly generates plausible demand scenarios and can be rapidly extended to new materials, regional aggregations, and socioeconomic scenarios; a trade projection method; country-level resolution or flexible aggregations thereof; and individual material model structures tailored to the specifics of each material's economy. Together, these features provide a flexible framework for exploring future material demand, circularity, and their interactions with climate mitigation.

The present paper provides the methods, model code, results, and data. Section 2 introduces common modeling methods, including the methodology for stock and trade extrapolations. Section 3 outlines the specifics of the three material models plastics, steel, and cement. Section 4 shows exemplary model results. Section 5 concludes with a summary and next steps. Section 6 briefly discusses model code and data availability.

2 Common model methods

This section describes the modelling framework common to all three materials and the methodological developments introduced in this paper. The first three subsections establish the general model approach, while the subsequent sections describe the specific innovations and the processing of input data. Detailed descriptions with equations on the stock and trade extrapolation methods are provided in the supplementary information (SI) Section S1.1 and S1.2, respectively. The SI also contains a section on trade adjustments (SI Section S1.3) not mentioned in the main text.

2.1 Scope and resolution

REMIND-MFA can be run with country-level resolution or arbitrary regional aggregations thereof. The results presented here are based on model runs with the 12-region aggregation of the REMIND IAM, (cf. Figure 4, panel a)). It is the level at which

validation of results was performed. The data on future demands and material flows published alongside this paper is provided both in country-level resolution and REMIND 12-region aggregation.

REMIND-MFA runs with annual resolution until 2100. The historical start year differs by material and is set to capture a good representation of the historical in-use stock build-up: For the older and more long-lived materials, cement and steel, the start year is 1880 and 1900, respectively, whereas for the more recent plastics with less long-lived stock, it is 1950. The transition from historical to future depends on the available data: The last historical year is 2024 for plastics, 2022 for steel, and 2025 for cement. All models normally run until 2100, but the model can be extended to 2150 without additional effort.

Apart from the region- and time dimensions, in-use stocks and adjacent flows are split by the category of end-use product they are contained in during use, such as vehicles or buildings. Further material-specific disaggregations are discussed in the material model descriptions, like polymer for plastics or differentiation between concrete and mortar in cement.

2.2 Basic model layout

A simplified common layout illustrating the general structure of the flows, processes and stocks in the different material MFAs is given in panel a) of Figure 1. The more complex layouts tailored to each material's specifics are given in Section 3. The central pillar of the MFA is the in-use stock. The pre-use branch of each MFA includes at least raw material production and the manufacture of end-use products. Both raw materials and end-use products may be traded. After use, materials can move to an obsolete or waste stock, or be recovered for recycling. Scrap material is also traded. Apart from additional processes, the detailed material models in Figure 3 include information on the disaggregation (i.e. the dimensions) of each flow, as well as all input data such as historical production volumes, recycling rates or end-use splits.

2.3 Model steps: Basic algorithm

Panel b) of Figure 1 shows the general workflow for each material. The core of the future demand scenarios is a projection of in-use stocks. This is a well-established approach because it is the stock of materials in use, rather than newly produced materials, that delivers services to society (Müller, 2006). Each material model in REMIND-MFA therefore consists of two dynamic MFAs, a historical and a prospective one. A historical MFA system computes the historical stock build-up based on production data: Since basic material production is quite homogeneous and takes place in a few large-scale plants, historical production data (0) has comparatively broad availability and high reliability. Translating production volumes into the flows entering the stock of end-use goods (1) includes historical trade flows at different stages in the supply chain, but also processing and fabrication losses. This flow is split into end-use good categories using shares from the literature. This stock inflow is then translated into build-up of historical stocks over time using an inflow-driven dynamic stock model (DSM) with a lifetime model (2). This provides historical stock build-up

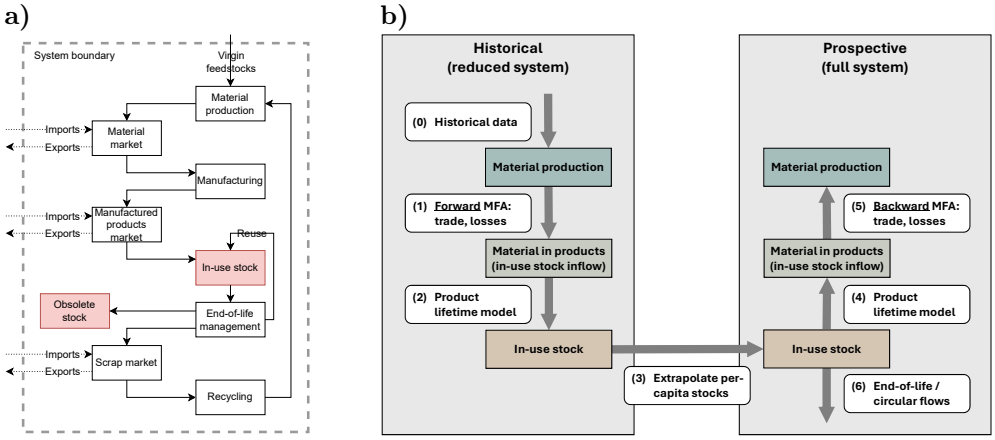


Fig. 1 a) Simplified common layout of REMIND-MFA. White boxes are processes, red boxes are stocks, arrows are flows. The model layouts of each material are given in Figure 3. They are more complex and tailored to each material's specifics. b) Model steps of REMIND-MFA. "Historical" and "Prospective" are two distinct MFA models, where the historical MFA is a reduced production-driven system and the prospective MFA is the full stock-driven MFA.

curves over time in every region. This historical build-up is projected into the future (3) using a novel method outlined in Section 2.4. The extrapolated stock is then used in a stock-driven dynamic stock model to yield the stock inflow (4). The MFA is calculated backwards from there, using the same losses and trades as described above, with trade flows extrapolated into the future using a methodology described in Section 2.5, to obtain future material production trajectories in every region (5). Circular and end-of-life flows are only calculated in the prospective system (6).

2.4 Stock extrapolation

A regionally differentiated stock projection algorithm is essential for demand projections (RQ1). It should continue region-specific historical trends, but also incorporate information from other regions, especially information on the relationship between economic growth and material stock growth, where data from developed economies can inform trajectories of developing economies.

Moreover, to be used flexibly in different coupled modeling frameworks (supporting RQ3), REMIND-MFA can run with arbitrary regional aggregations and automatically adapt to new socioeconomic background scenarios. To avoid excessive manual parameter adaptation, the stock extrapolation must therefore work without region-specific ad-hoc parameter guesses (like saturation levels or growth rates)[1].

To meet these two requirements, we developed a three-step stock extrapolation algorithm consisting of (1) common regression, (2) regional adaptation, and (3) transition smoothing. They are illustrated in Figure 2 and outlined below. The full equations are given in SI Section S1.1.

[1]Some region-specific adjustments can still improve the results, as no general model can fully replace expert knowledge about individual regions - but we show an adjustment-free version in this paper, to demonstrate the method's capabilities.

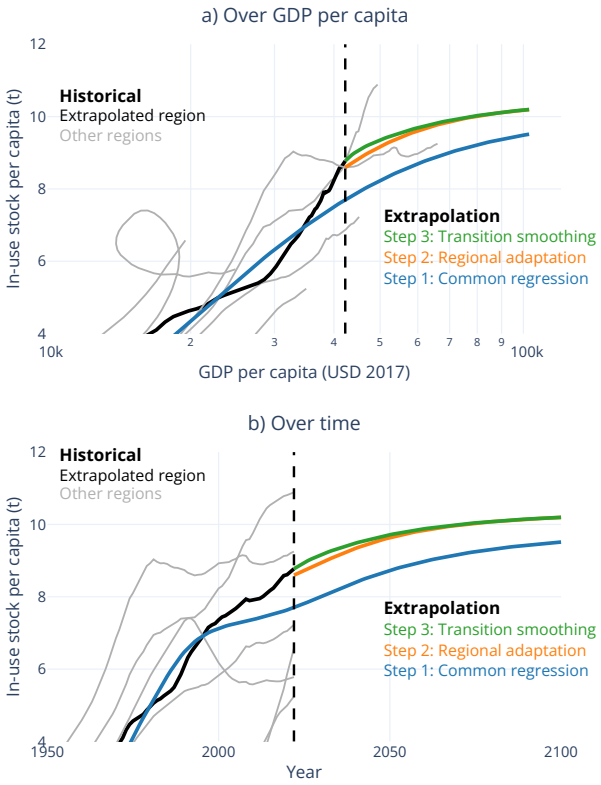


Fig. 2 The three steps of the stock extrapolation algorithm, illustrated for steel in Japan as an example. Panel a) is over GDP per capita (log scale), panel b) is over time.

Step 1: Common regression (blue line in Figure 2)

In-use stock per capita for every end-use category is regressed on the logarithm of GDP per capita using a logistic function. Future GDP and population trajectories are taken from the SSPs (Dellink et al., 2017), which ensures consistency of material demand trajectories with scenario variations there. Since material consumption shows signs of saturation, at least for steel and cement (Bleischwitz et al., 2018), the s-shaped logistic function is chosen to model in-use material stock developments. It is a common choice in the literature (Deng et al., 2023). The function and the effects of its three defining parameters are shown in SI Figure S1. The asymptotic total in-use material per capita is prescribed from expert judgement ("saturation level", i.e. the upper asymptote). For the SSP2 scenario, the prescribed values are 2 t/cap for plastics, 10 t/cap for steel, and 180 t concrete/cap for cement, which corresponds to about 24 t cement/cap at historical cement ratios. These are the only required material-specific scenario assumptions (one scalar value per material). The regression of the two remaining free parameters of the logistic function (growth rate, setting the curve steepness, and horizontal offset, shifting it along the GDP axis) is applied separately by end-use category, but jointly for all regions.

Step 2: Regional adaptation (orange line in Figure 2)

The parameters of the logistic function (saturation level, growth rate and offset) are altered regionally, to ensure consistency with historical trends, while still using knowledge about historically observed relationships of material stocks over GDP per capita. The adapted parameters are obtained by minimizing a penalty function over the adapted parameters, including penalty terms for (1) deviations of the parameters from the common regression, (2) deviations of the logistic function with the adapted parameters from recent historical data and its growth trend. The optimization results in an adapted logistic function for each region and end-use category, which balances similarity to inter-regional data and continuation of regional historical trends.

Step 3: Transition smoothing (green line in Figure 2)

Since differences from historical data are a soft criterion in the regional adaptation step, the adapted logistic curves may differ slightly from most recent historical data points both in terms of absolute stock values and growth rates. A smooth transition from historical data to the regressed future trajectories is therefore applied. The growth rate of the latest historical stock is also taken into consideration, to avoid jumps in stock inflow and, consequently, production. After running the stock-driven dynamic stock model, the same transition smoothing is applied to the stock inflows followed by an inflow-driven run of the dynamic stock model. A description and equations of the smoothing algorithm are given in SI Section S1.1.3.

2.5 Trade extrapolation

REMIND-MFA represents trade through markets at different stages of each material's supply chain. Bilateral trade is not represented; only aggregate imports and exports are tracked for each region, but not the trade partners. In the raw material and end-use product trade extrapolations, the respective future demand (for raw material, end-use products) is prescribed, so that the resulting trade volumes only influence the regional distribution of production. For steel scrap trade, supply is prescribed instead. Plastic waste trade is not extrapolated, but set exogenously in the scenario definition.

For the extrapolation, in each trade market, the share of imports in a region's respective demand is kept constant in the future. In other words, imports are assumed to grow in proportion to the respective demands. Similarly, the share of a region's production which is exported is kept constant, such that exports grow in proportion to production.

Several modifications are made to this general rule to account for cases where it falls short:

First, in some lower-income regions, current demands are very low and are projected to grow by several orders of magnitude. In these regions, historical trade shares have limited predictive power for the future; future trade shares are therefore informed by a mix of regional and global historical shares. Second, regions with shrinking demand and production often have existing written-off production facilities, such that they can be expected to produce at relatively low cost. In these regions, exports are

therefore kept constant instead of declining in proportion to production. This modification mostly applies to cement and steel in China, where despite a declining demand, exports are not expected to decline. Third, the transition from recent historical to future trends of both imports and exports is smoothed using the same algorithm as for stocks and stock inflows, as described in Section 2.4, Step 3. Fourth, after each region's future imports and exports are projected, they are summed globally. Both imports and exports are then scaled by a correction factor such that global imports equal global exports to fulfill the global mass balance.

Details on the trade model are provided in SI Section S1.2. A more elaborate trade model requires model components beyond MFA, such as based on regional production cost trajectories. An Armington trade model coupled to REMIND-MFA is under development.

2.6 Input data processing

The entire data-processing workflow, from raw data to standardized MFA inputs, is implemented in the open-source R package mrmfa, ensuring full reproducibility and transparency while facilitating continuous improvement. The package builds on madrat (Dietrich et al., 2025) and uses other input data packages from the Potsdam Integrated Assessment Modelling (piam) framework (Baumstark et al., 2020; Koch et al., 2026). It first processes all input data at the 249-country level and subsequently aggregates them into larger regions based on a single mapping file. The MFA itself is fully agnostic to the regional aggregation, making it effortless to implement alternative regional configurations.

2.7 AI support

The development of the REMIND-MFA model code was supported by AI coding agents. All AI-generated code was reviewed and verified by the authors.

3 Material models

The material models build on the common framework outlined above. However, life cycle characteristics, such as material fragmentation, emission sources and sinks, end uses, and recyclability differ substantially across plastics, steel, and cement. Each model therefore has an individual structure tailored to these characteristics, improving both demand projections (RQ1) and circularity assessments (RQ2). The three model layouts are shown in Figure 3 and briefly described in the following sections, covering dimensions, production, in-use stock, circular flows, and trade for each material. Complete definitions of the models, including processes, flows, stocks, and exogenous parameters, are provided in SI Section S2.

3.1 Plastics

Panel a) of Figure 3 shows the plastics MFA. It distinguishes eight end-use sectors and thirteen polymer types, capturing the sector's high material heterogeneity. *Production* is based on data from Plastics Europe (Plastics Europe, 2025), supplemented

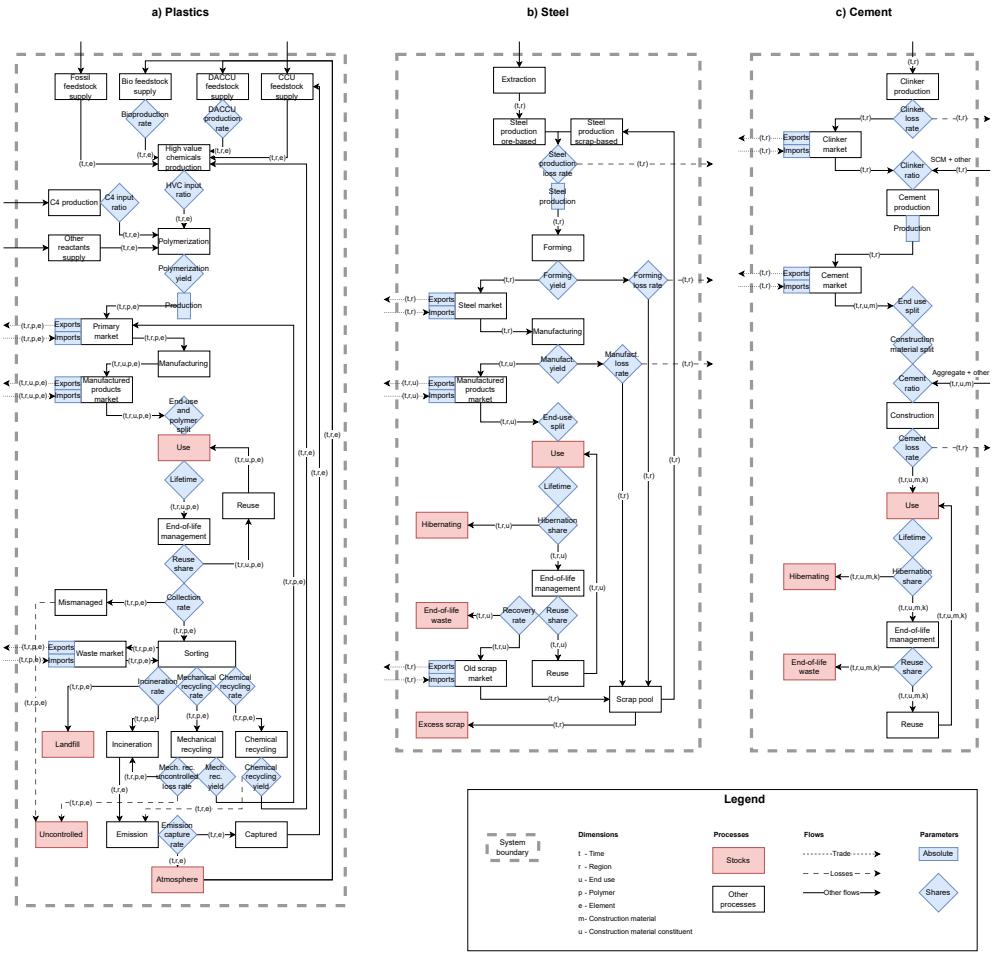


Fig. 3 Layouts and system definition for the three material MFA models.

with data from Textile Exchange (Textile Exchange, 2026) and Industrievereinigung Chemiefaser e.V. (IVC) (IVC, 2025) for synthetic fibre production, and the International Rubber Study Group (IRSG) for synthetic rubber production (IRSG, 2026). The representation of multiple feedstock sources (fossil, bio-based, recycled, and synthetically produced from direct air capture) enables embedded carbon emission balancing. The *in-use stock* extrapolation is augmented with a time-dependent growth term to reflect an ongoing expanding market penetration that is independent of GDP growth. Plastics MFAs often use an inflow-driven dynamic stock model due to mostly short end-use product lifetimes. We use a stock-driven model instead, which uses a sub-timestep quadrature of the lifetime function similar to the approach proposed in Cencic and Frühwirth (2025). This method ensures consistent flow-to-stock ratios even for short-lived applications, while the stock-based approach enables the assessment of circularity interventions based on lifetime extension, as well as temporary demand surges driven by the build-up of long-lived end-use stocks. *Circular flows*

include reuse, mechanical and chemical recycling alongside the non-circular end-of-life pathways incineration, landfilling, and mismanagement. The shares of these pathways are time-dependent and defined exogenously per scenario. Carbon flows including atmospheric carbon are consistently tracked across the system to ensure carbon-cycle balancing. *Trade* is implemented for raw materials, end-use products, and waste, with data from Gaulier and Zignago (2010) and UNEP (2020).

3.2 Steel

Panel b) of Figure 3 shows the steel MFA. It differentiates between four end-use sectors. *Production* covers the stages from crude steel production through forming and fabrication to final goods. Historical production data from World Steel Association (2023) is used. The *in-use stock* inflow is allocated across end-use sectors using shares approximated as a function of GDP per capita, which is informed by regional end use splits from the literature. *Circular flows* reflect the widespread recycling of steel scrap, representing scrap generation at three stages along the life cycle: Steel forming and manufacturing loss rates (Cullen et al., 2012) determine generation of home scrap and new scrap, while the outflow of the in-use stock, multiplied with scrap collection rates, drives the generation of old scrap. Recycling reintroduces scrap into production, but the share of secondary steel is capped at 70% of total production to reflect material quality limitations, while excess scrap accumulates in a separate stock. The historical model is calibrated against observed scrap use data from Bureau of International Recycling (2009–2024) through the adjustment of key parameters such as yields, lifetimes, and recovery rates, where parameters such as the collection rate are varied as a function of GDP per capita. Reuse is represented as well. *Trade* is represented for intermediates, end-use products, and scrap using data from World Steel Association (2023) and Gaulier and Zignago (2010).

3.3 Cement

The cement MFA is shown in Panel c) of Figure 3. Four end-use sectors and two application types (concrete and mortar) are distinguished. *Production* covers not only cement, but also explicitly represents clinker and end-use products. Historical cement production data are taken from Andrew (2019, 2026b). As clinker is the most carbon-intensive material in the value chain, material transformation coefficients represent key levers of circular economy intervention. The region-specific clinker-to-cement ratio is calculated based on clinker and cement production data (Andrew, 2019, 2026a, 2026b) wherever available, and informed by GCCA (2024) elsewhere. Application-specific cement intensities and material losses are based on unpublished data from Kaufmann et al. (2024). The in-use stock model is based on regionally differentiated data for both lifetimes and end-use shares (Kaufmann et al., 2024) further resolved by end use. *Circular flow* modeling reflects the limited recyclability of cement: Reuse of concrete elements is represented, while down- and recycling into aggregates and fines is out of scope and, in the latter case, implicitly assumed to play a role in reducing the clinker ratio. *Trade* is explicitly represented for clinker and cement using data

from Gaulier and Zignago (2010), while end-use products are treated as non-tradable, reflecting their fixed location.

4 Results

The results are structured around the three questions motivating REMIND-MFA. As a core result, we first address RQ1 by presenting per-capita in-use stock extrapolations and material production trajectories (Section 4.1). We then illustrate the model's capacity to address RQ2 through three more detailed applications: global plastics carbon flows (Section 4.2), future steel trade (Section 4.3), and regional cement production across scenarios (Section 4.4). Sections 4.1–4.3 show results for an SSP2 ("middle of the road") socioeconomic driver scenario under a current policies assumption, which serves as a baseline for further policy assessments such as in Section 4.4. For visualization, regional results are aggregated from the original 12-region set to the five regions shown in panel b) of Figure 4. Sections 4.2–4.4 show results for one representative material in the main text. Equivalent figures for the other materials are provided in SI Section S3 for all results, using both the five-region aggregation and the original 12-region set. The SI further contains a comparison of country-resolution and 12-region results (SI Section S3.8), as well as underlying population and per-capita GDP trajectories (SI Sections S3.6 and S3.7).

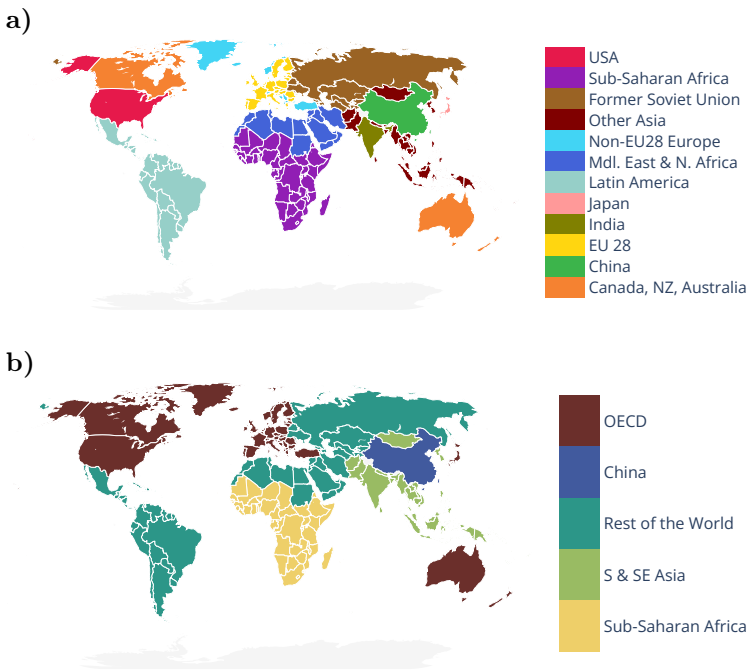


Fig. 4 a) Definition of the REMIND 12-region aggregation used for the model runs presented in this paper. The complete country mapping is given in Table S1 in the SI. b) Five-region aggregation for visualization purposes; the five regions are supersets of the REMIND 12-region aggregation in panel a).

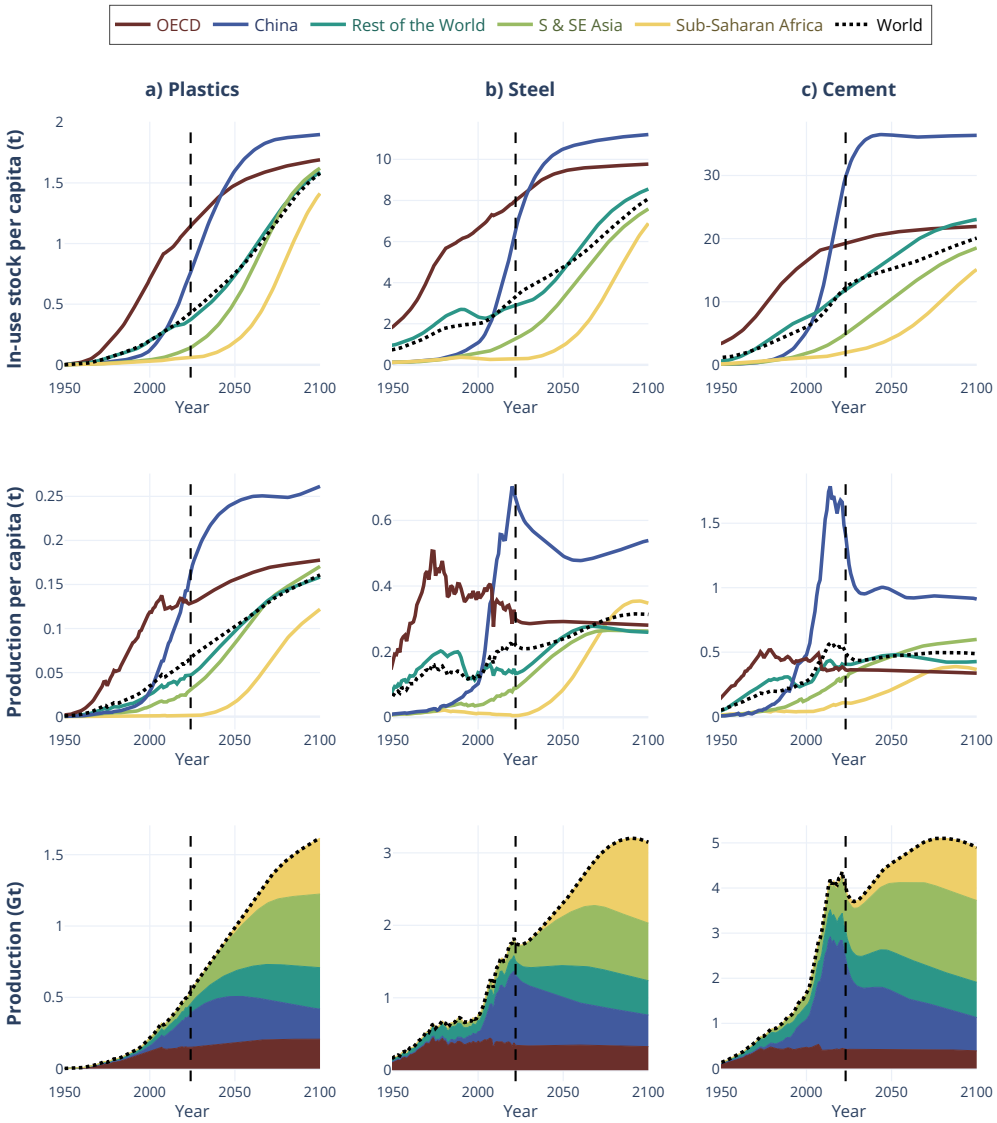


Fig. 5 In-use stock (top) and production (center and bottom) projections for plastics (left), steel (center), and cement (right) in the SSP2 current policies scenario. Vertical lines mark the last year with historical data; production refers to raw material production.

4.1 In-use stocks and demand projections

Figure 5 addresses RQ1 by showing past and projected developments of in-use stocks and production.

For plastics, a recent material with still expanding use, historical per-capita in-use stocks (top row in the figure) show no clear signs of saturation even in developed

economies. Future extrapolations for this scenario show growing per-capita stocks in all regions until the end of the century, with signs of saturation around the exogenously prescribed 2 t per capita. Lower-income regions approach the stock levels of higher-income regions over time.

The patterns for steel and cement are different from plastics: developed regions show signs of stock saturation (top row), while lower-income regions remain orders of magnitude below higher-income regions in recent times. Saturation of historical stocks is partly concealed by the regional aggregation - finer resolutions show it more clearly (cf. SI Figure S5). China shows rapid growth in the recent past. Future per-capita stock projections are mostly stagnant for developed regions, while lower-income regions converge towards similar levels as higher-income regions.

Global production (bottom row) increases substantially for all materials, with an almost three-fold increase in plastics. Steel and cement trajectories show a peak in China in recent years, making China the dominant producer in the recent period, followed by a projected decline in the coming decades. For all materials, the "South & Southeast Asia" and "Rest of the World" regions emerge as new major producers by 2060, with sub-Saharan Africa emerging as a further large producer toward the end of the century. The OECD share of global production diminishes sharply in all materials.

The future dominance of the Global South in absolute global production is not reflected in per-capita production (middle row), which remains at levels comparable to those of the OECD region. Convergence toward OECD levels, combined with the much larger and growing population share of the Global South, is sufficient to drive its higher absolute production.

The extrapolation produces smooth stock and production trajectories without needing region-specific future parameters based on expert judgement. The production trend break in China for steel and cement is no exception, as it is already visible in the most recent historical years. Regional narrowing of disparities in per capita in-use stocks is an explicit model feature: the regional adaptation penalizes differences in saturation levels. This is consistent with the regional convergence assumption underlying SSP2 and other SSP narratives, in particular converging GDP per capita in SSP2.

Taken together, these results imply a substantial future material-demand and equity challenge. Even with largely constant per-capita in-use stocks in the Global North, rising per-capita stocks in the Global South toward Global North levels, combined with population growth, lead to substantial increases in global demand. Limiting the associated climate and other environmental impacts requires consideration of both demand- and supply-side interventions.

4.2 Future carbon flows in plastics

Figure 6 provides a more detailed illustration relevant to RQ2 and RQ3, showing global carbon flows in the plastics life cycle in 2050. The in-use stock (dark grey) is still growing in 2050, as its carbon inflows exceed its outflows. Several options for closing carbon cycles are illustrated: In this scenario, mechanical recycling is the dominating strategy, while chemical recycling plays a minor role. Carbon capture and use, as well as plastics production from biomass, can also be interpreted as closing carbon cycles, albeit with the detour over atmospheric carbon. However, the measures taken in this

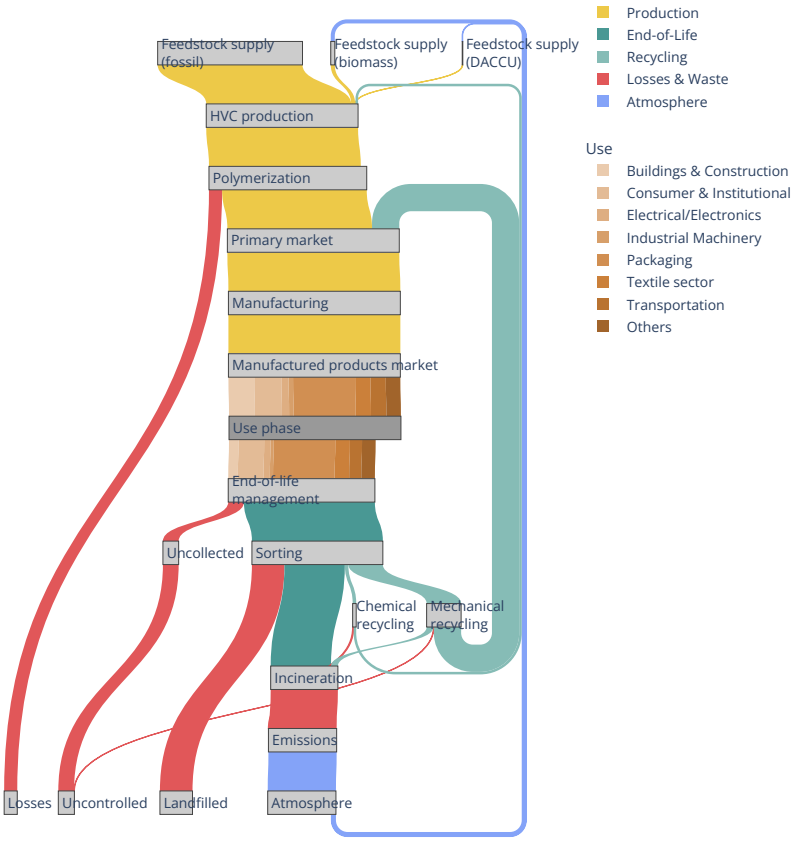


Fig. 6 Sankey diagram of the 2050 global embedded carbon cycle in plastics in an SSP2 current policies scenario; trades are omitted due to the global scope.

scenario are far from sufficient: The mass flow balance of the "Atmosphere" process indicates net-positive emissions from the plastics cycle due to waste incineration alone, even without accounting for production emissions.

4.3 Steel trade

Figure 7 illustrates how the trade extrapolation algorithm builds on demand projections. It shows future exports and imports of steel (UN COMTRADE HS chapters 72 and 73, i.e. excluding trade in end-use goods). In the OECD and China, where steel demand is stagnant or declining, absolute trade volumes (left-hand side in the figure) remain relatively constant over time. Regions of the Global South show the largest changes in trade flows, following the very large increases in demand. This occurs despite a decreasing import share (imports over demand, bottom right panel) in Sub-Saharan Africa, as the region's import shares converge towards the global average: Although the region currently heavily depends on imports, the implemented trade extrapolation algorithm assumes that it will shift towards domestic production with a growing economy, like all developed regions have in the past. Other trade shares

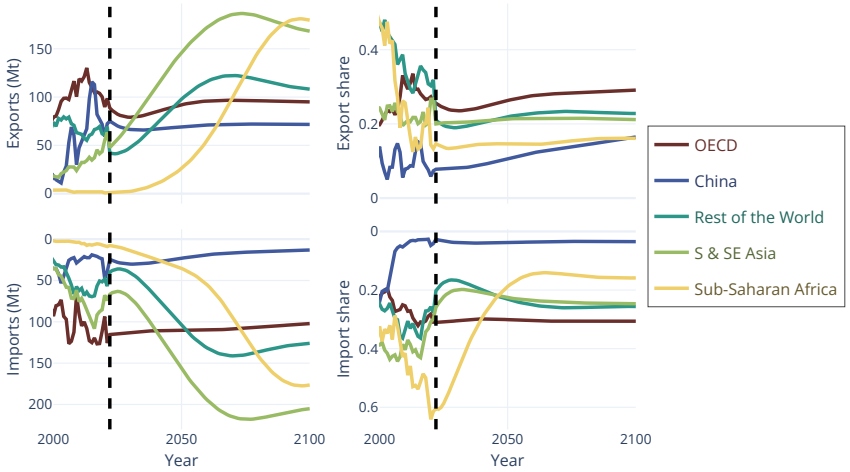


Fig. 7 Projected exports (top) and imports (bottom) of steel; left: absolute trade volumes; right: export share (exports divided by local production) and import share (imports divided by local demand). Vertical dashed lines denote the last year with historical data.

stay mostly constant, apart from an export share (exports over production, top right panel) increase in China due to its projected domestic demand decrease. These results illustrate the range of plausible developments generated by the trade algorithm, but future trade patterns remain highly uncertain.

4.4 Cement demand scenario variations

Figure 8 illustrates how socioeconomic and circularity assumptions translate into different material-demand trajectories, linking to RQ2. It compares the SSP2 baseline with two scenarios with a sustainability narrative: SSP1-drivers changes population and GDP trajectories according to the SSP1 projections (Dellink et al., 2017), while SSP1-CE (CE as in circular economy) additionally assumes a 10% reduction in in-use stock by the end of the century and a 20% increase in product lifetimes by 2060.

Comparing the SSP2 and SSP1-drivers scenarios shows the largest difference in developing regions, where the scenario differences in population and GDP are more substantial. In developed regions, only minor differences occur due to a lower projected population in SSP1 toward the end of the century. The further reductions of the SSP1-CE scenario compared to SSP1-drivers are quite uniform across regions, which is expected due to the uniform parameter changes. The results demonstrate how changes in socioeconomic drivers and circularity assumptions can be translated into consistent material-demand trajectories, providing the demand-side input needed to assess their implications for climate mitigation (RQ3).

5 Conclusion

We introduce REMIND-MFA, a global, top-down, economy-wide stock-driven prospective MFA model for the basic materials plastics, steel, and cement. Its complete

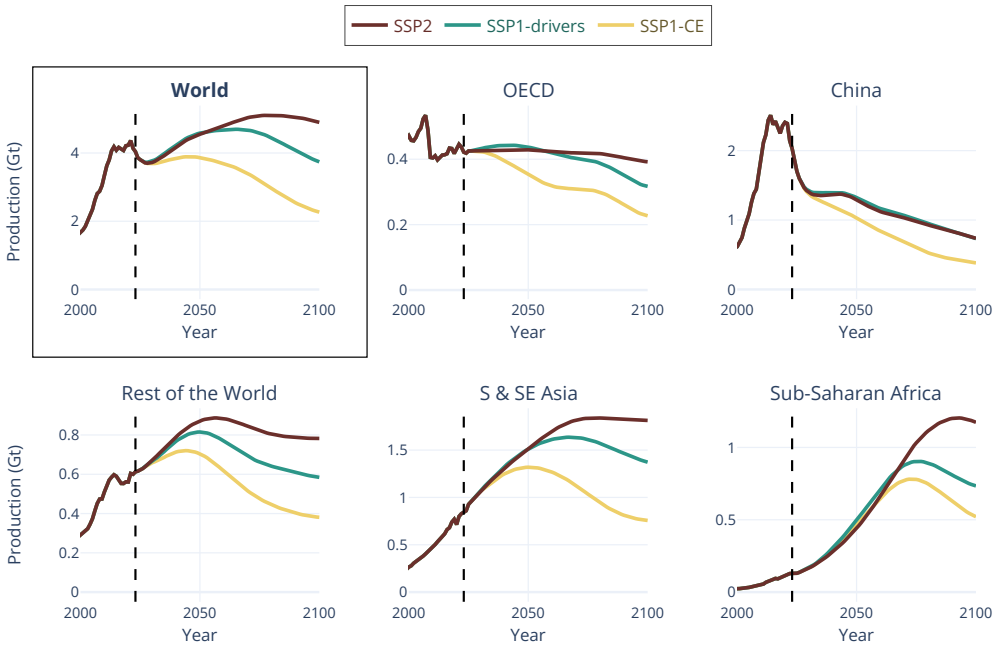


Fig. 8 Global and regional cement production across three different scenarios: SSP2 as a baseline, SSP1-drivers, where only GDP and population trajectories are adapted, and SSP1-CE where moderate circular economy (CE) measures are added to the scenario definition, consistent with the SSP1 narrative. Vertical dashed lines denote the last year with historical data.

regional and sectoral coverage enables comprehensive assessments of basic material demand implications on climate change. The model includes a novel in-use stock extrapolation algorithm built on SSP trajectories of GDP and population, which enables rapid and flexible generation of plausible material demand scenarios for different socio-economic background scenarios and regional aggregations. Trade patterns are projected using a simple novel algorithm. Tailored material models account for differences across sectors while preserving structural similarities.

Under the assumptions of global economic convergence and limited further intervention, the projected global basic material demand grows substantially through the end of the century, with serious environmental implications (RQ1). The detailed material-flow results illustrate the potential for circularity measures to reduce virgin material production and alter material flows (RQ2).

Model and data are open and published together with this paper.

Three factors determine the results and their reliability: input-data quality and resolution, scenario assumptions for inherently uncertain developments, and model structure.

Data: Production and trade data have good coverage and resolution, whereas end-use shares, lifetimes, and waste/scrap collection rates have limited availability on a regional level.

Scenarios: The present scenarios vary socioeconomic drivers, but parameters such as recycling rates and lifetimes are not yet fully incorporated into the SSP narratives.

Model Structure: Socioeconomic structures and their effects on regional per capita demand and production are implicitly captured by regional stock adaptation to historical data. Explicitly representing regional consumption preferences as well as production characteristics and costs could enhance model accuracy and scenario flexibility.

These limitations define the main directions for future development. The input data will be continuously updated and improved. Comprehensive scenarios regarding socioeconomic pathways and circular economy interventions will be derived based on literature-based potentials and plausible ranges. The model structure will be refined, modeling the largest end-use sectors based on service demands and residual demand retained in the top-down framework. This hybrid approach can increase sectoral detail without requiring exhaustive bottom-up data for all end uses. Moreover, trade scenarios will be informed by production cost data.

Finally, REMIND-MFA can support further analysis of climate mitigation and resource efficiency. A planned application is the coupling of these demand scenarios with the integrated assessment model REMIND. Such IAM coupling is needed to answer RQ3, enabling joint assessment of supply-side mitigation, demand-side measures, and circularity. Because REMIND represents industry, the energy system, and the wider economy, this coupling can assess mitigation options under constraints from limited resources and technology scale-up rates, as well as the effects of demand-side and circular-economy measures on emissions and mitigation feasibility.

6 Data and code availability

The complete model results are open and published along with the present paper https://doi.org/10.5281/zenodo.23804452. The data set covers the years 2025-2100, to avoid publishing proprietary historical input datasets. The publication includes model runs with the REMIND 12-region aggregation as well as with country-level resolution. Since input data availability is limited for some countries and vetting has only been performed on the REMIND-12 region level, the raw data in this dataset should be used with caution. However, users can perform their own regional aggregation on it. Regarding model input data, a subset is published (https://doi.org/10.5281/zenodo.18019915), since some data sources are proprietary or cannot be shared.

The REMIND-MFA code is open source at https://github.com/pik-piam/remind-mfa with documentation at https://remind-mfa.readthedocs.io/ (version v1.0.1 was used for this paper). It is written in Python. It is designed to be understandable, adaptable, and extensible by external users and developers. It is extensively documented. It is based on the flodym library (Dürrwächter et al., 2026). Runs can be configured using toml files, and new scenarios can easily be derived using scenario definition files. The scripts for figure, data and paper generation can be found in an extended repository version archived at https://doi.org/10.5281/zenodo.23805511. The input data generation package mrmfa is available under https://github.com/pik-piam/mrmfa (version v2.9.2 was used for this paper).

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