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China's Domestic Zinc Demand Transition to 2050: End-Use Structural Change and Future Stock-Flow Pathways

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Abstract

China's changing end-use patterns shape zinc demand, in-use stocks, and the timing and sources of zinc leaving use. A hybrid framework combining bottom-up and top-down projections with dynamic material flow analysis estimates domestic zinc demand, defined as annual zinc inflow to use, stocks and outflows through 2050 for 15 end-use subsectors representing specific applications, with results aggregated into six end-use sectors. The 2010–2020 reconstruction provides the basis for projections. Scenario analysis examines three socioeconomic pathways and two additional scenarios incorporating power-sector transition. Under the baseline scenario, annual zinc demand peaks at 6.58 Mt Zn/yr in 2045. By 2050, annual outflow reaches 6.00 Mt Zn/yr, approaching annual inflow of 6.37 Mt Zn/yr, while in-use stock reaches 104 Mt Zn. Building applications, automotive applications and industrial machinery and equipment generate substantial end-of-life zinc outflows, while power utility and machinery continue accumulating zinc stocks. Within buildings and infrastructure, growing zinc demand in power utility largely offsets declining demand in building applications. Power utility, automotive applications and industrial machinery and equipment together account for over half of national zinc demand in 2050. Estimating first-use zinc requirements from projected subsector zinc demand reveals modest changes in first-use category shares despite substantial shifts in end-use demand. Power-sector transition raises 2050 zinc demand by 9–10% relative to corresponding socioeconomic pathways, with much smaller outflow increases. The projected sources and timing of end-of-life zinc outflows can inform future assessments of secondary zinc availability.

Keywords

Zinc demand; Dynamic material flow analysis; Data reconciliation; China

Competing Interests

The authors declare no competing interests.

Data Availability Statement

The numerical data underlying the figures in the main article and Supporting Information are provided in the accompanying Supplementary Data spreadsheet. Additional supporting data is available upon reasonable request.

1. Introduction

Understanding how zinc demand changes in scale and composition is essential for assessing future primary-resource requirements, stock accumulation, and the availability of secondary zinc (Rostek et al., 2023). Zinc embodied in galvanized steel, alloys, and chemical products serves end-use sectors with different patterns of expansion, replacement, and material recovery, making end-use composition relevant to both secondary zinc availability and circularity (Meylan & Reck, 2017). The persistence of zinc in long-lived assets also separates the timing of demand from that of end-of-life (EoL) outflows: expanding stocks require zinc today while retired material becomes available for potential recovery only after zinc-bearing products leave use (Rostek et al., 2022). China plays a major role in the global zinc cycle, accounting for 49% of global refined zinc production and 51% of global refined zinc usage in 2023 (International Lead and Zinc Study Group, 2024). Demand for zinc in buildings, infrastructure, transport, and industrial equipment in China is substantial, while earlier development has already created large in-use zinc stocks (Rostek & Loibl, 2025; Tong et al., 2024).

Material flow analysis (MFA) studies have established how consumption, trade, stock accumulation, and recycling shape the anthropogenic zinc cycle across spatial and temporal scales. Meylan and Reck (2017) mapped national, regional, and global zinc cycles, identifying collection and waste-management losses as constraints on circularity. Maung et al. (2019) assessed secondary zinc resources across countries, distinguishing zinc accumulated in society from the portion considered recoverable through recycling under prevailing economic and technological conditions. Rostek et al. (2022) quantified the growth of global in-use zinc stocks and traced how new and old zinc-bearing scrap contribute to recycling; regional models subsequently revealed geographical differences in zinc consumption, stocks, and recovery through their trade connections (Rostek & Loibl, 2025). For China, Tong et al. (2024) documented expanding zinc use during 2000–2021, the predominance of galvanizing and construction, and manufacturing scrap as the main source for recycling. Gu et al. (2026) projected China's zinc flows and stocks through 2060, showing a declining construction-sector share of total zinc demand and different demand trajectories across end-use sectors. The projections indicated substantial increases in in-use zinc stocks and scrap generation between 2020 and 2040. Their assessment also linked these material flows to environmental impacts, identifying refining and galvanized products as major contributors and examining the benefits of improved recycling. Together, these studies establish the importance of accumulated stocks, trade, and recovery for zinc supply. Less is known about how zinc demand and stocks will redistribute among applications within China's major end-use sectors, and which applications will become important sources of EoL zinc.

Retrospective and prospective dynamic MFA (dMFA) both use material balance and product lifetimes to connect zinc inflows, stocks and outflows, but differ in how annual demand is determined: historical studies reconstruct flows from production, use, and trade statistics, whereas projections require assumptions about future demand or stock development (Müller et al., 2014). For China, Yan et al. (2013) extrapolated linear consumption trends for six zinc product groups over 2005–2020 and applied Weibull lifetime distributions to estimate scrap generation and recycling potential. At the global level, Rostek et al. (2023) fitted per-capita zinc

production in each first-use category against gross domestic product (GDP) per capita using 2000–2019 data. Power, logarithmic, or linear regressions were combined with economic and population projections to generate inputs for a dMFA model for 2020–2050 that compared recycling scenarios and the remaining need for mining. Taking a stock-driven approach, Gu et al. (2026) projected China's per-capita zinc stocks in five end-use sectors toward saturation levels informed by developed countries. Population projections, Weibull lifetimes, and regressions of historical imports and exports supported stock–flow and trade estimates through 2060. Tokimatsu et al. (2017) linked sectoral product demand and material intensities to economic and population scenarios to project demand for copper, zinc and lead. They then used a cost-minimizing mineral-balance model to assess primary and recycled supply over 2010-2150. Elshkaki et al. (2018) projected demand for seven major metals, including zinc, over 2010–2050 using growth rates linked to income and population, adjusted for urbanization and technological change, and compared demand with potential recycling and geological supply. These approaches connect demand to resource requirements, but projections based on first-use categories or broad end-use sectors do not fully distinguish the drivers of individual applications. Subsectors or specific applications within an end-use sector may follow different demand trajectories even when total sectoral demand changes little, and changing product composition can affect stock accumulation and the amount and timing of EoL outflows. Building on a full-life-cycle reconstruction of China's zinc flows and stocks for 2010–2020, this study projects domestic zinc demand for 2021–2050 across 15 end-use subsectors, with results aggregated into six end-use sectors. The hybrid framework combines bottom-up estimates of zinc-bearing product quantities, physical activity, and zinc intensity with top-down estimates of zinc inflow based on socioeconomic drivers, historical zinc consumption patterns and stock shares, and residual calculations. Within this framework, lifetime distributions and material balances are used to calculate zinc stocks and outflows from projected zinc inflows, or zinc inflows and outflows from projected zinc stock levels (Pauliuk & Heeren, 2020). Additionally, three socioeconomic pathways and two associated power-sector transition cases are used to examine alternative development paths and modelling assumptions with sensitivity analysis.

2. Methods

2.1. System boundary and analytical framework

The system covers zinc contained in materials and products within mainland China. The dMFA model reconstructs the historical zinc life cycle for 2010–2020 and links it to annual projections for 2021–2050. The historical boundary includes mining, refining, first-use fabrication, end-use manufacturing, use, and scrap treatment and recycling, with trade recorded at the relevant stages (Figure S1) (Rostek & Loibl, 2025). Six first-use categories are distinguished: galvanizing, die casting, brass, zinc semi-manufactures, chemicals, and miscellaneous, using a classification adapted from International Lead and Zinc Study Group (2024) and Rostek and Loibl (2025). Six end-use sectors are distinguished: buildings and infrastructure, transportation, industry, consumer goods, health and nutrition, and other. These end-use sectors comprise 15 subsectors, as detailed in Table S1. Each end-use subsector refers to a group of zinc-bearing materials, products and components associated with a particular application. Annual zinc inflows and outflows are

expressed in kt Zn/yr and in-use stocks in kt Zn. Use-phase inflow denotes zinc entering domestic use, which represents national zinc demand in this study. In-use stock denotes zinc contained in products that remain in domestic use at a given time. End-of-life (EoL) outflow denotes zinc leaving domestic use. For consumptive uses, zinc is accounted for as outflow in the year of use, without accumulation in in-use stocks.

The analytical workflow comprises retrospective reconstruction, subsector-specific future projections, scenario analysis, sensitivity analysis, and inter-comparison (Figure 1). For both the historical and future periods, the dMFA model calculates zinc stock and flow trajectories from annual inflow or stock estimates and lifetime distributions. Projection methods are selected according to the projection drivers of each subsector and data availability, drawing on the application-specific driver approach used by D. Dong et al. (2019) for copper demand in China. Drivers include physical product demand, product flows and socioeconomic indicators, with the subsector-specific methods and assumptions detailed in Section 2.4 and Table S3. Differences in these drivers and in product lifetimes shape the trajectories of zinc inflows, in-use stocks, and EoL outflows at the subsector level, which are then aggregated to sector totals. Future subsector projections are calibrated, where needed, to the reconstructed zinc inflows or in-use stocks for the base year, 2020. Products still in use in 2020 are included in subsequent calculations of stocks and outflows according to their ages and lifetime distributions.

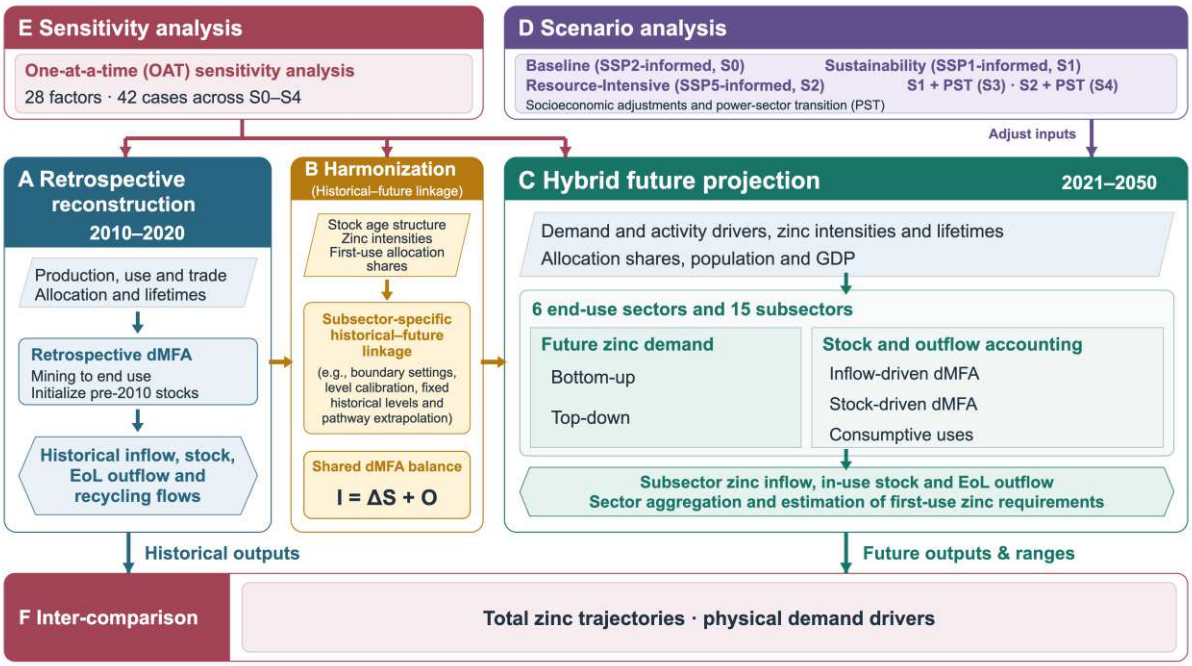

Figure 1. Analytical workflow of the dMFA of zinc in China. Subsector-specific harmonization connects retrospective reconstruction to hybrid projections. Distinct drivers and projection methods account for differences across 15 subsectors grouped into six end-use sectors. Subsector zinc trajectories are aggregated to sector totals, while zinc demand is used to estimate future first-use composition. The framework also includes scenario analysis, one-at-a-time sensitivity analysis and inter-comparison. dMFA, dynamic material flow analysis; EoL, end of life; GDP, gross domestic product; SSP, Shared Socioeconomic Pathways; PST, power sector transition; OAT, one-at-a-time. I denotes zinc inflow, ΔS the change in in-use zinc stock, and O zinc outflow.

2.2. Dynamic stock and flow modelling

A common cohort model connects zinc inflow, in-use stock, and EoL outflow in both historical and prospective calculations, using the DynamicStockModel routines in the Open Dynamic Material Systems (ODYM) framework (Pauliuk & Heeren, 2020). For subsector u and year t, the annual zinc balance is

$$I_{u,t} = S_{u,t} - S_{u,t-1} + O_{u,t} \quad (1)$$

Here $I_{u,t}$ and $O_{u,t}$ are annual zinc inflow and EoL outflow, respectively; $S_{u,t}$ is year-end in-use zinc stock, and $S_{u,t-1}$ is the previous year's stock. For an inflow-driven calculation, the inflow of each cohort is multiplied by its survival probability:

$$S_{u,t} = \sum_{\tau \le t} I_{u,\tau} \ell_{u,\tau}(t-\tau) \quad (2)$$

$$O_{u,t} = \sum_{\tau \le t} I_{u,\tau} [\ell_{u,\tau}(t-\tau-1) - \ell_{u,\tau}(t-\tau)] \quad (3)$$

Here τ is the year of entry into use and $\ell_{u,\tau}$ is the survival function, with survival before entry set to one. The summations cover all cohorts entering use by year t, and cohort age is $a = t - \tau$. In this study, the service lifetimes of zinc-bearing products in subsectors with durable stocks are assumed to follow normal distributions. The mean lifetimes and standard deviations are adopted from Rostek and Loibl (2025). For a cohort with age a, the survival function is

$$\ell_u(a) = 1 - \Phi\left(\frac{a - \mu_u}{\sigma_u}\right), \quad a \ge 0 \quad (4)$$

Here Φ is the standard normal cumulative distribution function, μ_u is the mean lifetime of zinc-bearing products in subsector u, and σ_u is its standard deviation. Table S3 lists the lifetime parameters. Cohorts already in use retain their historical lifetime distributions. In inflow-driven calculations, annual zinc inflows determine stocks and outflows; in stock-driven calculations, stock targets and surviving earlier cohorts determine the required new inflows (Müller et al., 2014; Pauliuk & Heeren, 2020). Agriculture, food and pharmaceutical, and industrial chemicals are treated as consumptive uses: zinc entering these subsectors is assumed to leave use in the year of entry, without accumulating in durable stocks. These outflows are not counted as old scrap in the model.

2.3. Retrospective zinc-cycle reconstruction

The historical zinc cycle for 2010–2020 is reconstructed using an inflow-driven dMFA model that combines production and trade statistics with process yields, first-use-to-end-use allocation, and product lifetimes. The zinc-cycle boundary, accounting and scrap matrices, process yields, and recycling parameters are adapted from Rostek and Loibl (2025). Zinc mine production and primary and secondary refined zinc production are obtained from the China chapters of the U.S. Geological Survey (USGS) Minerals Yearbook (U.S. Geological Survey, n.d.). Trade data for China, expressed as zinc mass, are taken from the compilation of Rostek and Loibl (2025), which is based on United Nations (UN) Comtrade (United Nations Statistics Division, n.d.). For each historical year, net trade in zinc contained in first-use goods and end-use goods is allocated

across first-use categories and end-use subsectors, respectively, in proportion to their shares of zinc in domestic output at the corresponding stage. Refined zinc production, net refined-zinc imports, and zinc content in directly reused scrap together determine zinc input to first-use fabrication. Direct reuse is assumed to remain constant at 500 kt Zn/yr throughout 2010–2020 (Rostek & Loibl, 2025). The allocation of refined zinc across first-use categories is reconstructed from published evidence for 2010 (Meylan & Reck, 2017), 2014 (Goodwin, 2015), 2017 (van Leeuwen, 2019), and 2021 (Tong et al., 2024). Absolute zinc inputs to each first-use category are linearly interpolated between these reference years and normalized to obtain annual shares for 2010–2020. Data sources and interpolation procedures are detailed in Sections S2 and S3.1 and Table S2 of the Supporting Information.

The accounting matrix allocates trade-adjusted first-use output to end-use manufacturing:

$$F_{u,t} = \sum_{i} a_{u|i,t}(Q_{i,t}^{\mathrm{dom}} + M_{i,t} - X_{i,t}) \quad (5)$$

Here i, u, and t index first-use categories, end-use subsectors, and years. $F_{u,t}$ is zinc input to end-use manufacturing in subsector u; $Q_{i,t}^{\mathrm{dom}}$, $M_{i,t}$, and $X_{i,t}$ are domestic output, imports, and exports of first-use goods in category i, respectively. All four quantities represent annual zinc mass flows (kt Zn/yr). The coefficient $a_{u|i,t}$ gives the share of zinc from first-use category i allocated to end-use subsector u in year t, with shares across subsectors summing to one for each category.

Manufacturing yields and end-use goods trade then determine the annual zinc inflow to domestic use, $I_{u,t}$. This inflow drives the calculation of in-use stocks and EoL outflows using the lifetime-based dMFA model described in Section 2.2. The amount of zinc in new scrap generated during first-use fabrication and end-use manufacturing is calculated from the respective process yields, with collection rates and separation efficiencies determining how much of this zinc enters recycling (Section S3.2). EoL zinc outflows are allocated to waste streams and use-phase zinc losses using the corresponding scrap matrix. The annual amount of zinc in processed old scrap is inferred from the downstream recycling balance: secondary refined zinc production and the enrichment yield determine the scrap required for secondary refining; adding assumed direct reuse and accounting for scrap trade gives domestic scrap processing demand, from which processed new scrap is subtracted. Old-scrap separation efficiencies then determine the collection required to supply this processing demand and the associated separation losses. The difference between the amount of zinc in theoretically collectable old scrap and the inferred amount is recorded as old scrap unaccounted for recycling (Figure S1).

The scrap matrix assigns zinc content in end-of-life products to waste streams (Rostek & Loibl, 2025; Rostek et al., 2022). Separation efficiencies specific to first-use categories and waste streams connect the zinc content entering separation to recovered old scrap and separation losses:

$$R_t^{\mathrm{sep}} = \sum_{i,w} W_{i,w,t}\eta_{i,w}^{\mathrm{sep}} \quad (6)$$

$$L_t^{\mathrm{sep}} = \sum_{i,w} W_{i,w,t} - R_t^{\mathrm{sep}} \quad (7)$$

Here $W_{i,w,t}$ is the amount of zinc in collected old scrap entering separation, indexed by first-use category i, waste stream w, and year t. The coefficient $\eta_{i,w}^{sep}$ is separation efficiency; R_t^{sep} is separated scrap and L_t^{sep} is the separation loss. Scrap inventories are not included. Zinc losses during scrap separation are calculated using separation efficiencies, while losses along the secondary refining route are calculated separately using the enrichment yield.

To account for zinc content in products already in use in 2010, the model includes zinc inflows from earlier years. Annual end-use sectoral zinc inflows and reference stocks for 1995–2009 are taken from Rostek and Loibl (2025). These sectoral inflows are allocated to subsectors using the inflow shares within each sector reconstructed for 2010. Zinc inflows before 1995 are estimated by comparing the reference zinc stocks with stocks calculated from inflows since 1995. The difference between these two stock series over 1995–2009 is used to estimate the contribution of zinc contained in products entering use before 1995 through bounded nonlinear least-squares optimization with penalties on deviations from a historical anchor, selected ordering relationships, and curve roughness. Both the reconstructed pre-1995 inflows and the inflows for 1995–2009 are included in the lifetime-based calculation of zinc stocks and EoL outflows during 2010–2020. The estimation procedures and equations are provided in Section S3.3 of the Supporting Information.

2.4. Hybrid future projection and harmonization

Future domestic zinc demand is projected for 15 end-use subsectors over 2021–2050. Here, zinc demand is defined as the annual zinc inflow associated with products entering use in China. This boundary connects future estimates to the reconstructed domestic-use zinc inflow and permits consistent comparison of demand, stocks, and outflows across scenarios. Future trade in end-use goods is not projected, so these estimates describe domestic-use requirements rather than the full zinc demand of manufacturing for export. The hybrid framework combines bottom-up and top-down estimates according to application-specific drivers and data availability (D. Dong et al., 2019). Projected zinc inflows or in-use zinc stock targets enter the corresponding dynamic material flow calculations, while consumptive uses have no durable stock. Table S3 and Sections S4.2–S4.7 provide the detailed calculations.

Bottom-up projections convert product quantities and physical activity into zinc inflows or in-use zinc stock targets using the corresponding zinc intensities. For building applications, projected annual construction floor area is derived from construction pathways or building floor-area stock targets (H. Li et al., 2026; Pauliuk et al., 2024; L. Zhang et al., 2023). For civil works, road-length projections are combined with road-specific zinc intensities to estimate in-use zinc stocks (Meijer et al., 2018; van Beers & Graedel, 2007), while vehicle-stock projections by type are combined with product masses and zinc fractions to estimate in-use zinc stocks for automotive applications (D. Dong et al., 2019; H. Li et al., 2025; Xu et al., 2025). Zinc inflow to power utility is calculated from gross additions of electricity-generation capacity (S. Zhang & Chen, 2026). For electronics, projected annual consumption of electrical and electronic equipment is combined with product masses and zinc fractions to estimate zinc inflow (Rostek & Loibl, 2025; Zeng et al., 2021; Zeng et al., 2020). The inflow-based zinc intensities for building applications

and power utility are held at their 2020 values to retain the base-year relationship between activity and zinc inflow. The resulting zinc inflows are used in inflow-driven dMFA, while the in-use zinc stock targets are used in stock-driven dMFA.

Top-down projections relate zinc inflow to socioeconomic drivers, including equipment investment and population. Equipment investment is used as the driver for the industrial machinery and equipment subsector, consistent with the role of machinery capital formation in metal demand (M. Jiang et al., 2023). A log–log regression relates zinc inflow to equipment investment, which is projected from 2026 using GDP and the fixed 2025 investment-to-GDP ratio. The consumer and general products subsector and the food and pharmaceutical subsector retain 2020 zinc inflow per capita and multiply it by scenario-specific population.

For the remaining smaller subsectors, top-down projections estimate future zinc inflows or in-use stock targets by holding historical inflow levels or stock proportions constant, extrapolating inflow trends, or calculating residual inflows from sector totals. The other transportation and containers subsector is linked to automotive applications through its historical stock share; plumbing retains its mean annual inflow for 2010–2020; and electrical power follows its historical inflow trend. Industrial chemicals, agriculture, and paint retain their 2020 inflows, while inflow to diverse uses is calculated as the mean total inflow of the other sector during 2016–2020 minus the fixed paint inflow. For quantities or shares held constant in these top-down projections, historical means are used when the series fluctuates around a relatively stable level; otherwise, base-year values are retained to represent recent conditions. Complementary historical-mean and base-year assumptions are compared in the sensitivity analysis. Using reconstructed 2020 zinc inflows as a benchmark, the subsectors covered by bottom-up projections, socioeconomic-driver-based top-down projections, and top-down estimates based directly on historical zinc inflows and stocks accounted for 64.3%, 19.2%, and 16.5% of domestic zinc inflow, respectively.

To estimate future first-use zinc requirements, projected zinc inflows to each end-use subsector are allocated among first-use categories using the subsector's reconstructed 2020 first-use shares. These shares are calculated as:

$$c_{i|u,2020} = \frac{I_{i,u,2020}}{I_{u,2020}} \tag{8}$$

Here, $I_{i,u,2020}$ is the reconstructed 2020 zinc inflow to subsector u associated with first-use category i, and $I_{u,2020}$ is the total zinc inflow to that subsector in 2020. The coefficient $c_{i|u,2020}$ therefore represents category i's share of subsector u's zinc inflow. Source shares within each subsector sum to one. Future inflows retain this composition:

$$I_{i,u,t} = c_{i|u,2020} I_{u,t}, \quad t \geq 2021 \tag{9}$$

The zinc required in first-use products is calculated by dividing these allocated zinc inflows by the corresponding manufacturing yields and summing across subsectors:

$$Q_{i,t} = \sum_{u} \frac{I_{i,u,t}}{y_{i,u,2020}}, \quad t \geq 2021 \tag{10}$$

Here, $Q_{i,t}$ is the annual amount of zinc required in first-use products of category i in year t (kt Zn/yr). The coefficient $y_{i,u,2020}$ is the 2020 manufacturing yield for category i and subsector u, defined as the fraction of zinc input retained in the manufactured end-use products. These yields are held constant for future projections. Total first-use zinc requirements and category shares are then calculated as:

$$Q_{\text{total},t} = \sum_i Q_{i,t} \tag{11}$$

$$p_{i,t} = \frac{Q_{i,t}}{Q_{\text{total},t}} \tag{12}$$

Here, $Q_{\text{total},t}$ is the total annual zinc requirement across all first-use categories in year t, and $p_{i,t}$ is category i's share of this total. Overall, first-use category shares can change as zinc inflows shift among end-use subsectors, even though each subsector retains its 2020 first-use composition. Figure 4 and Figure S2 report the resulting first-use zinc requirements and allocation. Future first-use requirements are calculated to meet projected domestic end-use zinc demand, without separately projecting imports and exports of end-use goods.

2.5. Scenario design

Three socioeconomic scenarios are defined in this study, informed by the Shared Socioeconomic Pathways (SSP; Riahi et al., 2017): S0 (Baseline, SSP2), S1 (Sustainability, SSP1), and S2 (Resource-Intensive, SSP5). Future population and GDP are projected from observed levels (data sources in Table S2) using relative changes in the corresponding SSP pathways (International Institute for Applied Systems Analysis, 2025). S1 uses the SSP1 pathways for annual construction floor area and passenger vehicle stocks (H. Li et al., 2025; Pauliuk et al., 2024). S2 derives annual construction floor area from SSP5 building stock projections and adjusts passenger vehicle stocks using the SSP5-to-SSP2 vehicle stock relationship reported by Shui et al. (2024). Scenario-specific road length pathways are used to project in-use zinc stocks in civil works (Meijer et al., 2018). Population pathways affect motorcycle stocks and zinc inflows to consumer and general products and food and pharmaceutical, while GDP pathways determine equipment investment for industrial machinery and equipment. Details are provided in Section S5 and Table S4.

Two additional scenarios incorporate power sector transition (PST): S3 extends S1 and S4 extends S2. They change technology-specific gross capacity additions and retirements in power utility and power-related equipment investment in industrial machinery and equipment, affecting zinc inflows to both subsectors. Capacity and investment pathways are taken from S. Zhang and Chen (2026), while coal and non-coal retirement assumptions follow Wang et al. (2025) and H. Dong et al. (2025), respectively. S3 follows the pathway to carbon neutrality across generation technologies with accelerated retirement; S4 retains the reference pathway for fossil fuel power generation and follows the pathway to carbon neutrality for non-fossil technologies. Comparisons of S3 with S1 and S4 with S2 illustrate the effects of power sector transition on projected zinc trajectories. Detailed assumptions and calculations are provided in Section S5 and Table S4.

2.6. Sensitivity analysis and inter-comparison

For each scenario, one-at-a-time (OAT) sensitivity analysis examines 28 factors through 42 alternative cases. Each alternative is compared with the reference calculation using that scenario's original parameters and assumptions. The tests cover product lifetimes, zinc intensities, reference values used to project zinc demand and stocks, historical reconstruction of zinc inflows, direct reuse of zinc from scrap, and first-use category shares. Percentage changes quantify the responses of zinc inflow, in-use stock, and EoL outflow; annual minimum–maximum ranges summarize variation across the 41 alternative cases for the 27 factors that affect inflow, stock, or outflow. The test of first-use composition within each end-use subsector leaves projected end-use zinc trajectories unchanged. The design and parameter settings are given in Section S6 and Table S5, with individual responses and annual ranges in Figures S3–S4.

Inter-comparison with published studies considers national zinc trajectories and the physical drivers used to project subsector zinc demand. Historical and prospective comparisons use matched years, units, and system boundaries wherever possible. The historical estimates are compared with Rostek and Loibl (2025), recognizing shared methods and inputs. Strictly comparable prospective studies of China's zinc flows and stocks remain limited. Historical and projected zinc inflows, stocks, and outflows are therefore compared with Gu et al. (2026). Additional literature evaluates the major building, infrastructure, and transport drivers. The results are summarized in Table 1 and discussed in Section 4.1.

2.7. Use of generative artificial intelligence

ChatGPT and Codex, both provided by OpenAI, were used to assist with developing and debugging model code, processing data, implementing visualization code, and revising manuscript text. Figures were generated programmatically from source data and model outputs. The authors take responsibility for the model assumptions, interpretation of results, and final manuscript.

3. Results

3.1. Projected zinc demand peak and a narrowing inflow–outflow gap

China's in-use zinc stock accumulated rapidly during 2010–2020 as annual inflow remained above outflow throughout the decade (Figure 2). Inflow fluctuated between 4.86 and 5.55 Mt Zn/yr, peaking in 2015 before returning to 5.12 Mt Zn/yr in 2020. Stock nevertheless rose from 33.8 to 65.5 Mt Zn. Over the same period, outflow increased from 1.20 to 2.84 Mt Zn/yr. The historical trajectory therefore combines substantial in-use zinc stock growth with an expanding flow of zinc leaving use.

Under the baseline scenario, projected EoL zinc outflow approaches annual zinc inflow by 2050, slowing stock accumulation while demand remains substantial (Figure 2). Zinc inflow peaks at 6.58 Mt Zn/yr in 2045 and reaches 6.37 Mt Zn/yr in 2050, while outflow rises to 6.00 Mt Zn/yr. The annual net zinc stock addition consequently falls from 2.28 Mt Zn in 2020 to 0.37 Mt Zn in 2050, although total stock continues to increase to 104 Mt Zn.

The subsectors accumulating zinc most rapidly are not necessarily the largest sources of EoL zinc before 2050, because retirement depends on service life and when products entered use. Zinc stock in building applications peaks in 2033, after which zinc outflow exceeds inflow as earlier construction cohorts retire and new demand declines. This decline is consistent with slowing new construction and lower future demand for building materials in China (Lu et al., 2024). Zinc used in automotive applications approaches an inflow–outflow balance near 2050 as vehicle-stock growth slows and retirements increase (H. Li et al., 2025). In power utility and industrial machinery and equipment subsectors, zinc stocks continue to accumulate. By 2050, zinc outflows from building applications, automotive applications, and industrial machinery and equipment each reach approximately 1 Mt Zn/yr, compared with 0.61 Mt Zn/yr from power utility.

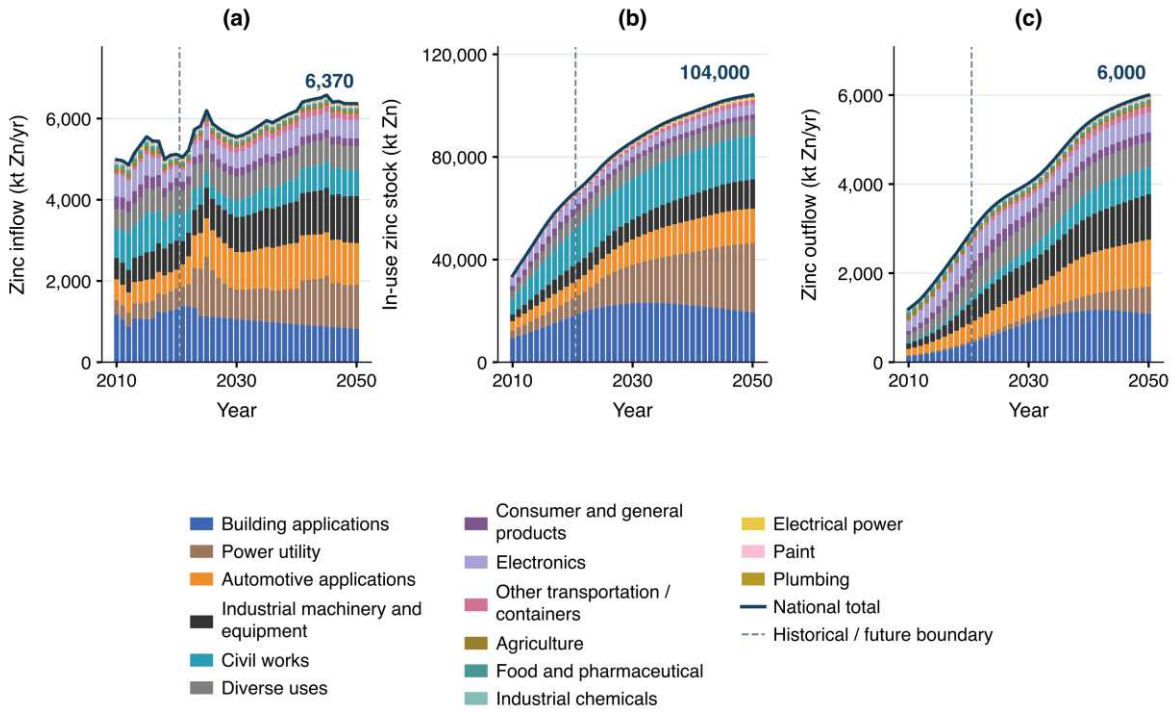

Figure 2. Annual zinc trajectories by end-use subsector under the baseline scenario, 2010–2050: (a) inflow, (b) in-use stock, and (c) outflow. Stacked bars sum to the national totals, shown by the navy lines; dashed lines separate historical reconstruction (2010–2020) from projection (2021–2050).

3.2. Contrasting subsector trajectories and the changing composition of zinc demand

By 2050, zinc demand is less concentrated in buildings and infrastructure, while this sector continues to hold most of the in-use zinc stock (Figure 3). This sector remains the largest destination for annual zinc inflow, although its share falls from 51% in 2020 to 41% in 2050 as its absolute demand changes little. Transportation and industry each account for approximately 18% of national zinc demand in 2050, compared with about 10% and 15% in 2020. The buildings and infrastructure sector still holds roughly 60% of national in-use zinc stock, reflecting the large quantity of zinc already installed and the long service lives of these assets.

Subsectors within the same end-use sector show contrasting zinc demand and stock trajectories, particularly within buildings and infrastructure (Figures 2 and 3). The share of building applications in national zinc demand declines from about one-quarter in 2020 to one-eighth in 2050, while growing demand in power utility largely offsets declining demand in building applications within the sector. In-use zinc stock in building applications peaks during the 2030s, whereas stock in power utility continues to accumulate. Across all subsectors, power utility in buildings and infrastructure, automotive applications in transportation, and industrial machinery and equipment in industry together account for just over half of national zinc demand in 2050, up from about 33% in 2020 (Figure 2a). The growing role of machinery is consistent with evidence that investment in machinery capital is an important driver of metal use (M. Jiang et al., 2023).

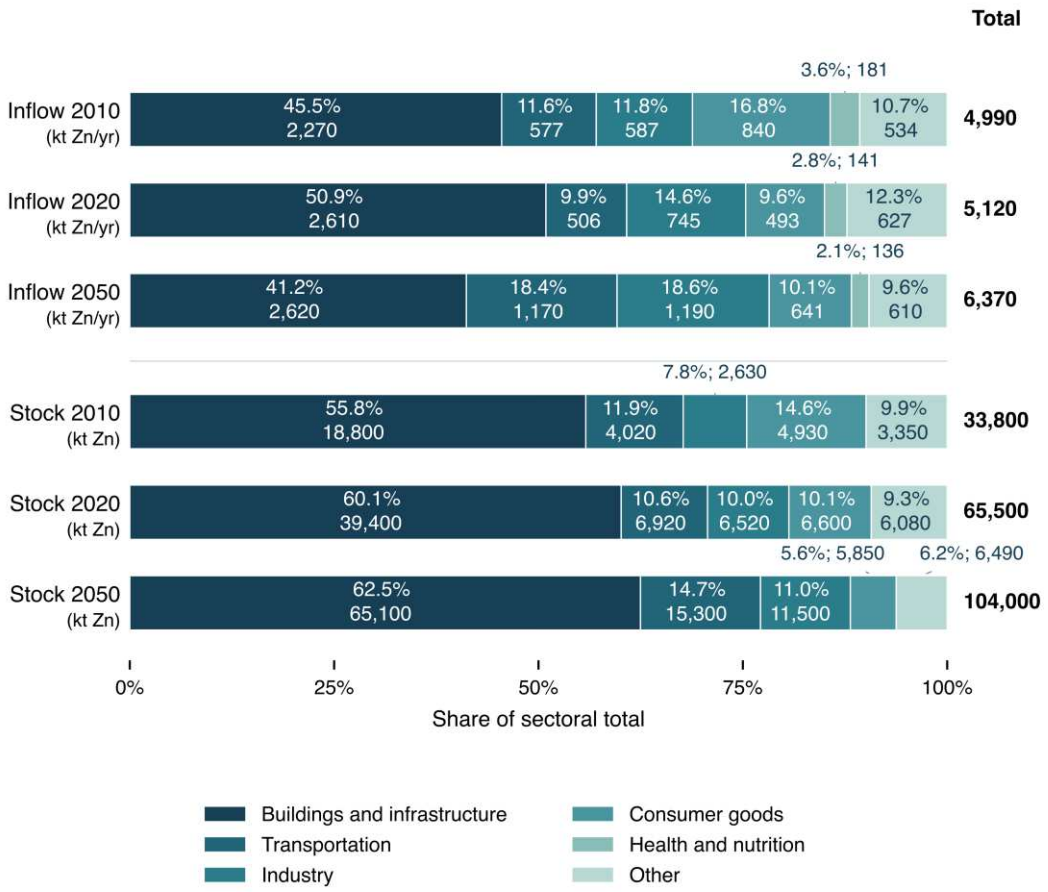

Figure 3. Sectoral composition of annual zinc inflow and in-use stock in 2010, 2020, and 2050 (baseline projection). Labels report both sector shares and absolute zinc quantities; national totals are shown on the right.

3.3. Stable first-use shares accompany changing end-use destinations

The shift in end-use zinc demand produces relatively modest changes in aggregate first-use shares but marked changes in the end-use applications requiring each first-use product (Figure 4). Future first-use zinc requirements for domestic use are estimated with an assumption of zero

net trade in end-use goods. Galvanizing remains dominant, with its share of first-use zinc requirements declining from about 65% in 2020 to 62% in 2050, while brass and chemicals gain share (Figure S2). Larger changes occur in the end-use allocation of zinc in semis and chemicals: the share allocated to automotive applications increases in both categories, while the share allocated to building applications declines for semis.

Galvanizing accounts for the largest share of total first-use zinc requirements in both 2020 and 2050, making zinc in galvanized products a representative case for examining changes in end-use zinc demand. The end-use allocation of zinc in galvanized products shifts from building applications toward power utility and automotive applications (Figure S2). The share allocated to building applications falls from 34% in 2020 to 18% in 2050, while the share allocated to automotive applications approximately doubles from 6% to 12%. Power utility becomes the largest destination for zinc in galvanized products. These changes reflect shifts in zinc demand across end-use subsectors, even though the first-use category shares of each subsector's zinc inflow remain fixed at their 2020 values.

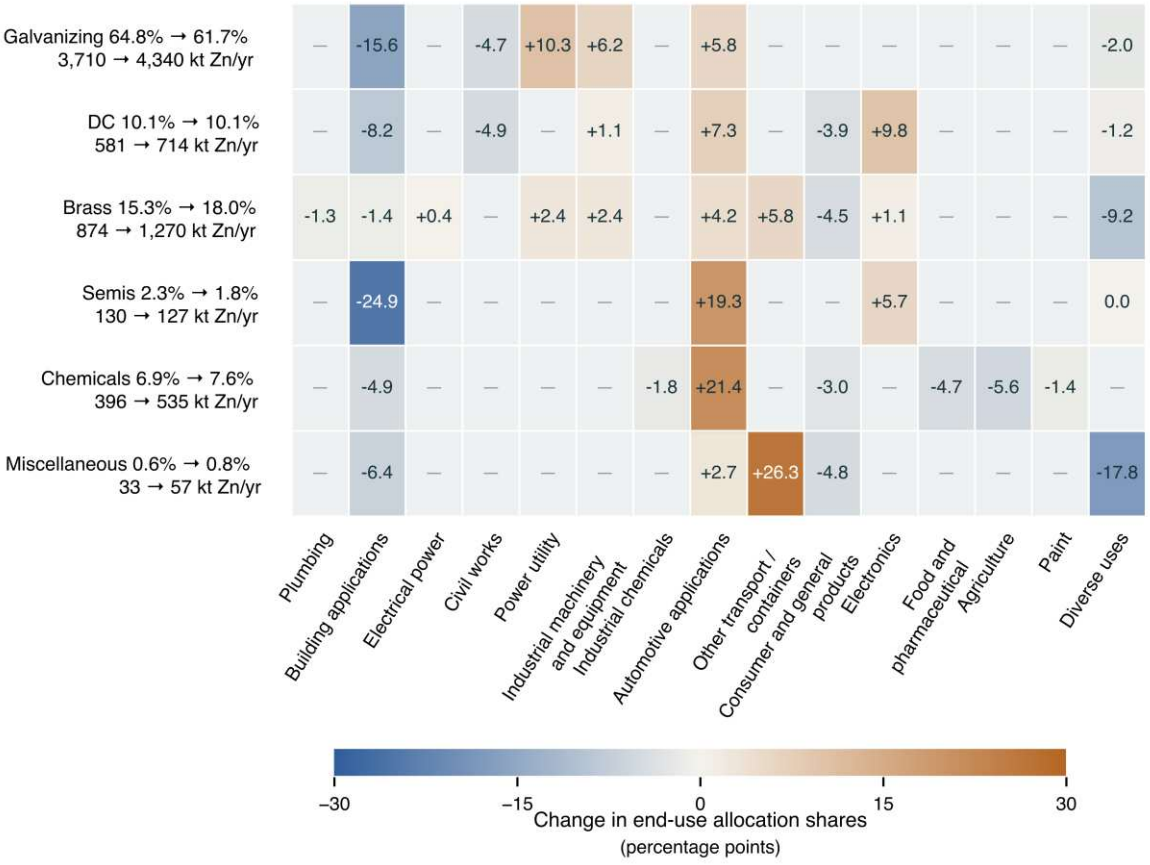

Figure 4. Changes in the shares of zinc allocated from each first-use category to end-use subsectors between 2020 and 2050 (baseline projection). Row labels report each category's share of total first-use zinc requirements and its annual zinc quantity (2020 → 2050). Quantities represent zinc in first-use products required for domestic end use. Within each category, cell values show the 2050 end-use allocation share minus the 2020 share, in percentage points. Blue indicates decreases and orange increases; darker shades show larger changes. Gray cells with dashes indicate structural zeros in both years. DC, die casting; semis, zinc semi-manufactures.

3.4. Power sector transition increases zinc demand more than EoL outflow by 2050

Over the projection period, socioeconomic development pathways generally produce larger relative changes in annual zinc demand than in in-use stocks and EoL outflows (Figure 5). Changes in building activity, transport demand, and economic drivers affect new zinc inflows before their full effects emerge in zinc stocks and outflows. Relative to the Baseline scenario (S0), the Sustainability scenario (S1) reduces total zinc inflow by 1.7% in 2030, with the difference narrowing to 0.3% in 2050. The Resource-Intensive scenario (S2) increases zinc demand in the later years, raising 2050 zinc inflow by 4.4%, while its zinc stock and outflow remain less than 1% above S0. The differences therefore depend on the timing and composition of zinc demand changes within each development pathway.

Power-sector transition adds zinc demand under both socioeconomic pathways, while much of the corresponding scrap becomes available only after the new assets have served their useful lives. Adding the transition to the Sustainability scenario (S3 relative to S1) raises 2050 zinc inflow by 9.8%; adding it to the Resource-Intensive scenario (S4 relative to S2) raises zinc inflow by 8.9%. The higher percentage increase in S3 partly reflects the lower zinc inflow in its parent scenario, S1, while total inflow remains higher in S4. In both comparisons, additional power installations and associated equipment increase in-use zinc stock by about 7%, but outflow by less than 1%. The additional zinc demand is consistent with the increased material requirements projected for China's power sector transition towards carbon neutrality (H. Dong et al., 2025). For these power-related applications, zinc outflow remains substantially below inflow within the projection period, as much of the newly installed equipment remains in use through 2050.

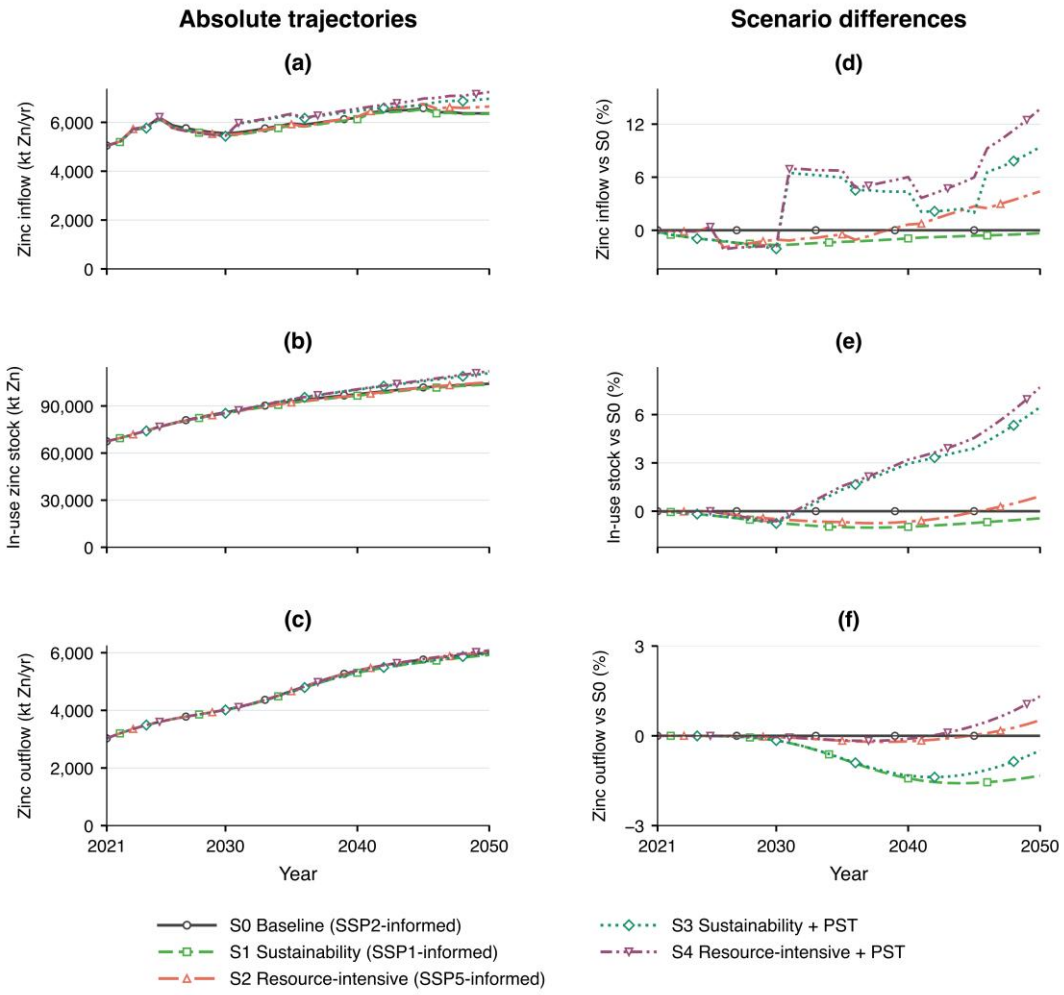

Figure 5. Projected zinc trajectories under scenarios S0–S4, 2021–2050. Panels (a–c) show absolute zinc inflow (demand), in-use stock, and outflow, respectively; panels (d–f) show the corresponding percentage differences from S0, calculated as 100 × (scenario / S0 − 1). Colors, line styles, and markers distinguish scenarios. The right-hand panels use different percentage scales. SSP, Shared Socioeconomic Pathways; PST, power sector transition.

3.5. Zinc intensity and lifetime assumptions shape projected zinc inflows, stocks, and outflows

Zinc intensity has the strongest tested influence on 2050 baseline national zinc demand and the upper bound of the in-use stock range (Figure 6; Figure S3). For building applications and power utility, zinc intensities are calibrated from historical zinc inflow per unit of completed floor area and gross additions to power generation capacity, respectively. Replacing the 2020 power utility intensity with its higher 2010–2020 weighted mean raises national zinc inflow by 5.8% and stock by 8.3% in 2050. Using the historical weighted mean intensity for building applications reduces inflow by 1.8% and stock by 2.5%. Among lifetime tests, the largest variation in national zinc stock occurs for building applications (−4.1% to +4.4%). The power utility lifetime tests determine the 2050 range of EoL zinc outflow (−2.6% to +2.9%).

Power sector transition increases the sensitivity of projected zinc trajectories to power utility assumptions. Using the historical weighted mean intensity for power utility raises 2050 zinc inflow by 7.8–8.2% and stock by 9.8–9.9% in S3–S4, compared with 5.5–5.8% and 8.2–8.3%, respectively, in S0–S2. Power utility lifetime tests determine both 2050 outflow bounds in every scenario, with ranges of approximately −3.0% to +3.7% in S3 and −2.9% to +3.6% in S4. The lower stock bound results from shorter lifetimes in building applications under S0–S3 and in power utility under S4. These ranges reflect changes in one factor at a time. Across the five scenarios, the upper stock bound is determined by longer lifetimes in building applications through 2027 and by the historical weighted mean intensity for power utility from 2028. The lifetime factors determining the outflow bounds shift from building applications to civil works and then to power utility (Figure S4; Table S6).

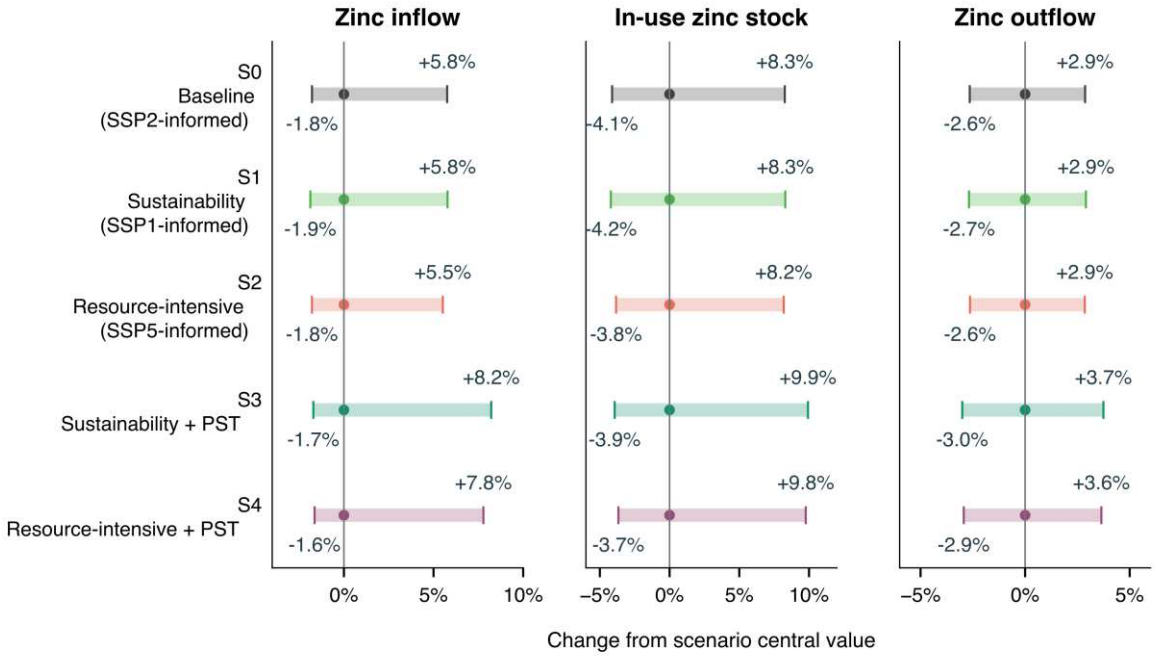

Figure 6. One-at-a-time sensitivity ranges for zinc inflow, in-use stock, and outflow in 2050 under scenarios S0-S4. Dots mark each scenario's central value (0%); bar ends indicate the minimum and maximum percentage deviations from that value across the tested cases, including the reference calculation. SSP, Shared Socioeconomic Pathways; PST, power sector transition.

4. Discussion

4.1. Inter-comparison

The plausibility of the projections is assessed through comparison with published estimates at two levels: national zinc demand trajectories and the physical demand drivers underlying subsector-level zinc demand projections (Table 1). The 2020 zinc inflow, in-use stock, and outflow estimates differ from Rostek and Loibl (2025) by +2.2%, +0.1%, and −0.9%, respectively. This close agreement reflects methodological inheritance and shared inputs: the historical reconstruction draws on their zinc-cycle framework and allocation, recycling, and

lifetime parameters, while estimating the annual shares of zinc input allocated to each first-use category in China.

Prospective studies of China's zinc flows and stocks with comparable system boundaries and time horizons remain limited. The study by Gu et al. (2026) provides a reference for comparing both historical estimates and future projections. Compared with that study, the domestic-use zinc inflows estimated here are lower, reflecting differences in historical data, process boundaries, and projection methods (Table 1). The historical reconstruction accounts for zinc losses during first-use fabrication, end-use manufacturing, and scrap separation, although the definitions of these stages differ between the two studies. It also estimates larger net exports of zinc in goods, particularly at the end-use stage, and less zinc in recovered old scrap, with further differences in secondary refining and direct reuse. Although total use-stage zinc outflows are similar in 2020, differences in historical inflows carry forward into future stock estimates. Projected zinc trajectories also reflect differences between the driver-based projection approach adopted in this study and Gu et al.'s sectoral stock-saturation approach. Lower cumulative zinc inflows lead to lower projected stocks, while lower future zinc inflows into shorter-lived applications contribute to lower outflows.

The main physical drivers of zinc demand fall within selected literature ranges despite differences in end-use classifications. Table 1 compares historical and projected new building floor area, including separate 2050 residential and nonresidential estimates (Deetman et al., 2020; Lu et al., 2024; You et al., 2025), and passenger vehicle stocks across studies and scenarios (Duan et al., 2025; Meng et al., 2026; Yu et al., 2024). These comparisons support the plausibility of these driver estimates. However, historical agreement partly reflects shared statistical sources, and similar physical drivers can still yield different zinc demand estimates when zinc intensities differ.

Table 1 Inter-comparison of zinc trajectories and physical demand drivers

Indicator	This study	Literature value / range	Difference (%) / position	Sources
1 Total zinc trajectories				
2020 zinc inflow, stock and outflow				
Inflow (Mt Zn/yr)	5.12	5.01	+2.2%	
In-use stock (Mt Zn)	65.5	65.4	+0.1%	(Rostek & Loibl, 2025)
Outflow (Mt Zn/yr)	2.84	2.86	-0.9%	
Inflow (Mt Zn/yr)	5.12	6.33	-19.1%	
In-use stock (Mt Zn)	65.5	72.3	-9.4%	(Gu et al., 2026)
Outflow (Mt Zn/yr)	2.84	2.83	+0.3%	
2040 zinc inflow, stock and outflow				
Inflow (Mt Zn/yr)	6.19	7.70	-19.6%	
In-use stock (Mt Zn)	97.5	133	-26.6%	(Gu et al., 2026)
Outflow (Mt Zn/yr)	5.38	6.69	-19.6%	
Stock peak year	Not by 2050	2044	Different years	(Gu et al., 2026)
Stock maximum (Mt Zn)	104	134		
2 Physical drivers				
2020 new floor area (million m²/yr)				
All buildings	3,850	2,040–3,850	Within	(Deetman et al., 2020; Hong et al., 2014; Y. Jiang et al., 2023; Lu et al., 2024; Ren et al., 2025; Xia et al., 2025)
2050 new floor area (million m²/yr)				
All buildings	2,440	780–7,500	Within	(Chen et al., 2026; Deetman et al., 2020; Hong et al., 2016; Hong et al., 2014; Lu et al., 2024; Xiao et al., 2023; You et al., 2025)
Residential	1,790	680–2,970	Within	
Nonresidential	649	100–650	Within	
Passenger-vehicle stock (million vehicles)				
2020	242	228–242	Within	(Duan et al., 2025; Huang et al., 2026; Meng et al., 2026)
2030	423	310–472	Within	(Duan et al., 2025; Y. Li et al., 2022; Meng et al., 2026; Ou et al., 2021; Peng, Ou, et al., 2018; Peng, Yuan, et al., 2018; Song et al., 2021; Xue et al., 2019; Yu et al., 2024)
2040	565	382–586	Within	
2050	605	359–900	Within	

Notes: Point differences are calculated as 100 × (this study / literature − 1). "Within" indicates that this study's estimate falls within the reported literature range, including its bounds. Literature ranges show the minimum and maximum values reported across the cited studies and scenarios.

4.2. Implications for circularity and zinc production

The historical zinc cycle shows substantial scope to improve recovery before the larger future zinc outflows become available (Figure 7). In 2020, galvanizing dominated zinc in first-use output at 4.20 Mt Zn/yr, and the buildings and infrastructure sector received 2.61 Mt Zn/yr of end-use zinc inflow. These patterns reflect the importance of galvanized products and construction in China's zinc use (Tong et al., 2024). Yet only 0.53 Mt Zn/yr, representing 18.7%

of total EoL zinc outflow, reached the separated old-scrap stream, while 1.67 Mt Zn/yr remained unaccounted for recycling. The latter nevertheless highlights the importance of improving collection and tracing discarded zinc-bearing products (Rostek & Loibl, 2025).

As national zinc outflow approaches inflow, the potential secondary resource could cover a growing share of demand, if collection and recovery improve. The subsector results identify its sources and timing: building applications shift toward net stock release during the 2030s, while automotive applications and industrial machinery and equipment become substantial sources of EoL zinc outflow before 2050. Material recovered from these applications could help meet the growing requirements of power assets and machinery. Realizing this connection requires collection and treatment capacity suited to the retiring products, as well as recovery routes that deliver zinc in forms suitable for subsequent manufacturing (Rostek et al., 2023).

In addition, the projected shares of total first-use zinc requirements remain relatively stable despite shifts in end-use zinc demand. These requirements are estimated from projected domestic end-use demand, accounting for manufacturing losses and assuming zero net trade in future end-use goods. Although applications demand different quantities of zinc from first-use products, galvanizing remains dominant and the first-use share changes moderately. This supports planning around established fabrication routes while adapting products to new destinations, such as the shift from buildings toward vehicles and power assets. The inference is consistent with the use of zinc for corrosion protection across housing, transport, and energy infrastructure (International Zinc Association, 2024). The relatively stable first-use composition may provide a more stable demand structure for upstream zinc production, including refining, helping producers adapt to changes in end-use demand.

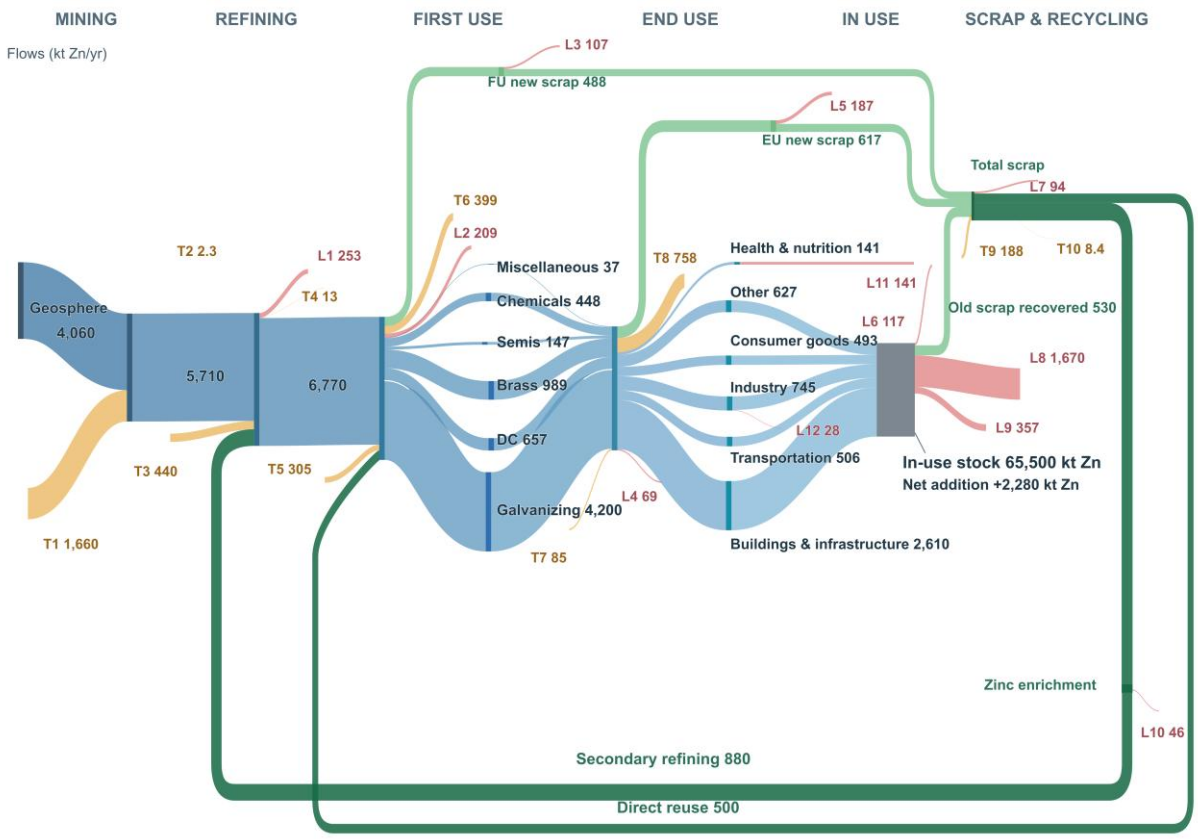

Figure 7. China's zinc flows and in-use stock in 2020. All quantities refer to zinc content. Blue denotes forward flows, yellow trade, red losses and old scrap unaccounted for recycling, light green scrap sources, and dark green recycling routes. The total-scrap node combines separated new scrap, recovered old scrap, and scrap imports. Trade labels T1–T10 denote concentrate import and export, refined-zinc import and export, first-use goods import and export, end-use goods import and export, and scrap import and export, respectively. Labels L1–L12 denote refining, first-use fabrication, first-use new-scrap separation, end-use manufacturing, end-use new-scrap separation, in-use dissipation and abandonment, traded-scrap separation, old scrap unaccounted for recycling, old-scrap separation, zinc enrichment, health and nutrition dissipation, and industry dissipation, respectively. FU, first use; EU, end use; DC, die casting; semis, zinc semi-manufactures.

Furthermore, shifts between applications can sustain substantial long-term zinc demand even as some established uses mature. Declining zinc demand for building applications and slower growth in vehicle stocks coexist with expanding requirements for power utility and industrial machinery and equipment. Related research also projects a declining construction share alongside growth in other zinc uses (Gu et al., 2026), while machinery investment represents a substantial source of metal demand more broadly (M. Jiang et al., 2023). In the present scenarios, these changes support continued zinc demand through 2050, with a changing distribution of demand across end-use applications. For the zinc supply chain, this suggests continued zinc demand alongside a need to adapt to growing applications. In this context, zinc demand from growing applications could partly be met by zinc recovered from retiring assets in mature applications, linking potential zinc recovery with changing end-use demand.

4.3. Limitations and directions for future research

Future trade impact is outside the scope of this study, as we focus on zinc entering domestic use and the resulting stocks and retirements within China. For future estimation of first-use requirements, zero net trade in zinc-containing end-use goods is assumed, so domestic manufacturing requirements equal domestic-use requirements at this boundary. Imports, exports, and their product composition could alter actual domestic manufacturing and first-use production requirements. A further extension could link domestic use to bilateral trade in concentrates, refined zinc, and zinc in first-use products, manufactured goods, and scrap. Existing zinc-cycle studies demonstrate the importance of these flows for domestic production and consumption (Meylan & Reck, 2017; Tong et al., 2024). Future trade flows could be projected at each life-cycle stage under scenarios specifying domestic production levels, import sources, and export destinations, with historical trade trends informing these assumptions (Gervais et al., 2025; Gu et al., 2026). This would clarify how alternative trade patterns affect domestic production requirements and the location of subsequent stocks and scrap generation.

The prospective calculations quantify use-stage zinc inflow, stocks, and EoL outflows by subsector and estimate first-use zinc requirements from end-use zinc demand. These outflows identify the sources and timing of potential secondary resources; actual zinc recovery is outside the scope of the present projections. Therefore, future recycling modelling could build on the historical framework by disaggregating subsector EoL zinc outflows by first-use category and allocating them to waste streams (Rostek & Loibl, 2025). Future collection rates could be specified as scenario inputs, alongside waste-stream-specific separation efficiencies, processing routes, and recovery yields. Product-level differences in recovery, including those for galvanized products, warrant explicit treatment (Yan et al., 2013). Scenarios could examine improvements in these parameters and changes in treatment routes to estimate zinc returned through secondary refining or direct reuse (Rostek et al., 2023). This would help assess the contributions of retiring buildings, vehicles, and other products to future zinc requirements.

5. Conclusions

This study develops a hybrid demand-side framework combining bottom-up and top-down methods to project China's zinc trajectories across 15 end-use subsectors representing specific applications, with results aggregated into six end-use sectors. Historical reconstruction provides the basis for future projections. Together with a dynamic material flow analysis model, these projections reveal contrasting zinc trajectories among applications. Under the baseline scenario, annual zinc demand peaks at 6.58 Mt Zn/yr in 2045. By 2050, end-of-life zinc outflow reaches 6.00 Mt Zn/yr, approaching annual inflow of 6.37 Mt Zn/yr, while stock accumulation slows down. Building applications, automotive applications, and industrial machinery and equipment have become major sources of end-of-life zinc outflows. Power utility and machinery continue to accumulate zinc stocks. Zinc demand becomes less concentrated in buildings and infrastructure, where growing demand in power utility largely offsets declining demand in building applications. This sector nevertheless retains roughly 60% of national in-use zinc stock. Power

utility, automotive applications, and industrial machinery and equipment from three different end-use sectors, together account for over half of national zinc demand in 2050.

For first-use producers, this study suggests that the composition of first-use zinc requirements will remain relatively stable, even as demand shifts among end-use applications. Growing zinc demand in power utility and machinery may sustain national demand as demand in building applications declines and vehicle stock growth slows. Power sector transition raises 2050 zinc demand by 9–10% relative to corresponding socioeconomic pathways, with much smaller increases in outflow. China's historically old scrap unaccounted for recycling highlights the need for improved waste collection and tracking, while projected subsector zinc outflows identify the origins and timing of potential secondary resources.

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