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Measuring carrying capacity of steel material from the perspective of closed-loop supply chain

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Abstract

Steel production is integral to the global economy; however, the sector is confronting significant material limitations. Previous studies on carrying capacity have primarily adopted a macro-level perspective, lacking frameworks applicable at the enterprise level. The interrelationship between closed-loop supply chains (CLSCs) and carrying capacity is not well-defined. Here we extended the theory of carrying capacity to micro-enterprises operating within CLSCs. Steel material carrying capacity is defined as the maximum sustainable production scale and operational duration that a steel firm can maintain under given technological, resource-supply, and CLSC-management conditions, encompassing both short-term annual resource throughput and long-term material availability horizon. Employing material flow analysis, the Hubbert peak theory, sigmoid demand modeling, and multi-scenario simulation, a quantitative framework for assessing steel carrying capacity has been formulated. Reductions in carrying capacity are predominantly driven by upstream beneficiation and smelting losses. Projections indicate that China's steel stock will reach its peak in scrap generation approximately in 2030. Enhancing the scrap recycling is paramount; a 10% increase in this rate is projected to decrease cumulative primary iron ore demand by 14.7% over a ten-year period. Calibration against firm-level data from three major Chinese steel producers confirms the robustness of the framework and reveals heterogeneous carrying-capacity improvement potentials across firms. This work introduces a methodology for evaluating steel carrying capacity at the micro-enterprise level, thereby contributing to material sustainability.

Introduction

Iron and steel are the core strategic foundational material underpinning China's national economic development. As the foundational industrial commodity, the assured provision of steel represents a critical determinant for the sustained functionality of China's ferrous metallurgy sector[1]. The iron and steel industry are also the largest carbon-emitting metal sector, bearing the dual strategic value of resource security and environmental protection.

Nowadays, Chinese iron and steel enterprises widely face three serious practical pressures. First, the external dependence on virgin iron ore remains high, and continuous fluctuations in international market prices keep squeezing enterprises' profit margins[2]. Second, China's steel scrap management has undergone four stages since 1949[3], but the recycling system is imperfect, leaving a large amount of scrap resources unable to effectively return to production[4]. Third, environmental protection policies are increasingly tightened, and the traditional linear "extraction-production-discarding" model can no longer meet sustainable development, leading to rising environmental compliance costs for enterprises[5].

In 2025, five Chinese ministries and commissions jointly issued the Work Plan for Steady Growth of the Iron and Steel Industry (2025-2026), which clearly supports comprehensive resource utilization and standardized development of scrap steel recycling[6]. The plan requires enterprises to shift from passive response to active layout, and pursue transformation to a closed-loop supply chain (CLSC) to enhance independent resource security. CLSC, consisting of forward logistics and reverse logistic[7], provides a

new solution for enterprises to break through resource constraints through material circularity via reuse, recycling and remanufacturing[8]. Our research group has employed this approach for numerous metals like lithium[9], cobalt[10], lead[11], nickel[12], copper[13], aluminum[14], and germanium[15]. However, existing practices and related studies mostly focus on single-link optimization of the supply chain or macro industry-level analysis[16,17], and rarely combine CLSC operation with carrying capacity evaluation from the micro enterprise perspective.

The above practical dilemmas faced by steel enterprises are essentially the manifestation of insufficient resource carrying capacity at the micro enterprise level. However, existing carrying capacity studies have long been limited to the macro level, and cannot provide targeted theoretical guidance and quantitative tools for enterprise operation decisions. Meanwhile, although CLSC has been recognized as the core path to alleviate material constraints, the intrinsic mechanism of how CLSC improves carrying capacity has not been systematically elucidated.

This study is rooted in the interdisciplinary evolution of carrying capacity and CLSC theory. Yet two core theoretical gaps still exist in existing research and the practical needs of steel enterprises. First, the application of carrying capacity has long been limited to the macro level and solely for primary resources. This theory has been extended to mineral and steel industry studies at national, regional and industry scales, forming a systematic macro evaluation system[18]. However, no mature theoretical paradigm, in light of secondary resource (e.g., steel scrap) supply, has been established for measuring steel carrying capacity from the micro enterprise level. Most existing studies take static virgin resource reserves as the core evaluation benchmark, ignoring the dynamic reshaping influence of scrap recycling on carrying capacity[19]. Second, there is a lack of in-depth coupling between CLSC theory and carrying capacity theory. Existing studies have confirmed that CLSC management can reduce virgin resource consumption and improve operational resilience of steel enterprises[5]. But most only focus on single-link operation optimization of the supply chain, and fail to reveal the driving mechanism of full-chain closed-loop management. The crucial question of how CLSC fundamentally reshapes the resource supply pattern of steel enterprises has not been answered theoretically[20].

To address these gaps, we first formalize the conceptual foundation of this study. Steel resource carrying capacity, at the macro level, refers to the maximum production scale and operational duration that a steel industrial system can sustainably support under given technological levels, resource supply conditions, and environmental constraints, traditionally evaluated against static primary resource reserves. We extend this concept to the micro enterprise level and define enterprise steel resource carrying capacity (ESRCC) as the maximum sustainable production scale and operational duration that an individual steel enterprise can maintain under its specific process structure, resource acquisition capability, and CLSC management level. ESRCC comprises two interdependent dimensions: (i) short-term carrying capacity—the annual throughput of primary and secondary resources that can be secured to support a given production capacity; and (ii) long-term carrying capacity—the time horizon over which accessible resource stocks can sustain continuous operation. Unlike macro-level assessments that treat

resource endowments as exogenous, ESRCC is endogenous to enterprise decisions: investments in reverse logistics, scrap pre-treatment, and beneficiation technology directly alter both dimensions. The comprehensive scrap recycling rate is identified as the core regulatory variable that connects CLSC operation to ESRCC improvement.

Totally, previous studies lack an integrated multi-method system linking macro laws to micro enterprise decisions. Material flow analysis (MFA), Hubbert peak model and S-shaped demand evolution rule have been widely used in steel industry research separately[16,21]. But these methods are often isolated from each other, and cannot form an entire framework to quantify the improvement effect of CLSC on carrying capacity. To fill these gaps, this work innovatively extends the macro resource carrying capacity theory to micro steel enterprises from the CLSC perspective, and constructs a quantitative evaluation system for enterprise steel resource carrying capacity. The introduction of the carrying capacity perspective into dynamic MFA is justified by the need to translate material flow efficiencies—traditionally reported as sector-level throughput metrics—into firm-level operational capabilities that directly inform investment, procurement, and capacity-planning decisions.

Results

Evolution characteristics of steel industry full-chain material flow

MFA of China's steel industry from 2010 to 2020 reveals a structural transition from a linear "high extraction-high emission-low recycling" model toward a closed-loop "moderate extraction-process reduction-end recycling" model. Fig. 1 presents the full-chain material flow diagrams for the three benchmark years, providing a direct visualization of the evolving resource metabolism pattern. Rather than merely documenting sector-level flow changes, the following analysis traces how each structural shift in the industry's material metabolism reshapes the resource supply boundary of individual steel enterprises and thereby alters their carrying capacity.

Fig. 1. Full-chain material flow of China's steel industry under a closed-loop supply framework (unit: Mt/yr): (a) 2010; (b) 2015; (c) 2020. Note: The closed-loop supply system comprises three recycling tiers —in-house production scrap internal circulation, fabrication (new) scrap recovery, and end-of-life (old) scrap return from social stocks. Solid arrows denote forward logistics; dashed arrows denote reverse recycling flows.

Iron ore input into the steel production system increased from 614.0 Mt in 2010 to 787.7 Mt in 2015, and further to 1043.5 Mt in 2020. The 32.5% increase from 2015 to 2020 significantly outpaced the growth rate of crude steel output, indicating declining ore grade and intensified pressure on beneficiation systems. This trend directly elevates the primary resource consumption intensity per unit of enterprise output and constitutes the core source of implicit depreciation in enterprise resource carrying capacity: front-end beneficiation and smelting losses—tailings, slag, and other solid wastes—represent primary

resources that have already incurred full extraction, transportation, and processing costs yet cannot be converted into effective output, causing permanent depreciation of carrying capacity. Solid waste generation in production surged from 247.2 Mt in 2010 to 1093.2 Mt in 2015, with tailings discharge peaking at 643.1 Mt in 2015. Although tailings data are not directly displayed in the 2020 diagram, inference from the iron ore input-concentrate output differential confirms that tailings generation remained at an elevated level. The node carrying-capacity depreciation coefficient (CDC) for the beneficiation-smelting cluster reached 28.6% in 2015, far exceeding the CDC values of downstream processing (3.2%) and end-use (1.8%) nodes, confirming that front-end losses are the dominant driver of carrying-capacity depreciation.

China's social in-use steel stock has accumulated rapidly. Net stock additions reached 495.8 Mt in 2010 and 643.1 Mt in 2015, with the accumulation effect intensifying through 2020. This trajectory indicates that China is in a steel material accumulation phase, and these stock resources will progressively enter their end-of-life phase over the next 10-20 years. From the enterprise carrying-capacity perspective, this accumulating social stock represents the core potential resource pool for closed-loop supply systems: the first scrap generation peak is projected around 2030, providing a critical time window for enterprises to deploy reverse logistics networks and expand scrap recycling capacity. Every ton of recycled steel scrap could save 1,134 kg of iron ore, 635 kg of coal, and 54 kg of limestone[22], directly reducing the primary resource throughput required per unit of output and thereby extending long-term carrying capacity.

The structural evolution of scrap recycling further substantiates the ongoing transition toward an endogenous resource supply model. Following the implementation of the waste import ban policy in 2017, China's steel scrap imports declined from 5.9 Mt in 2010 and 2.3 Mt in 2015 to a mere 0.026 Mt in 2020, effectively eliminating external scrap supply. Concurrently, total domestic scrap recovery grew from 27.7 Mt in 2010 to 95.3 Mt in 2020, with the share of post-consumer (old) scrap rising markedly. This shift signals that China's steel enterprises are transitioning from a resource supply model dependent on imported virgin ore and imported scrap toward one anchored in domestic social stock circulation. Nevertheless, the comprehensive scrap utilization rate remains below optimal levels relative to crude steel output of 1043.5 Mt, and scrap quality constraints—particularly impurity content and residual alloy elements—continue to limit large-scale application in high-end steel production. For enterprises, this implies that the carrying-capacity upside from CLSC investment remains substantial and is currently constrained more by reverse-logistics infrastructure and pre-treatment technology than by the physical availability of scrap.

Evolution mechanism and forecasting of China's steel demand

The long-term evolution boundary of steel demand constitutes the foundational input for enterprise resource carrying-capacity assessment. Rather than reproducing sector-level demand projections—an

extensively covered topic in existing literature—this section establishes the demand boundary and, crucially, demonstrates the mapping logic from macro industry demand laws to micro enterprise-level parameters.

The Hubbert peak model fitting of China's cumulative steel production reveals a characteristic S-shaped growth trajectory (Fig. 2a), divisible into three phases: an initial slow-growth phase (pre-2000), a rapid-rise phase (2000-2030), and a saturation-stabilization phase (post-2030). Cumulative steel demand is projected to approach its saturation point around 2050, with a total cumulative volume of approximately 28-30 billion tonnes. The demand growth inflection point is identified around 2030, after which the growth rate will decelerate substantially. This inflection point coincides temporally with the projected first peak in social scrap generation, marking the strategic turning point at which enterprises can transition from primary-resource dependence to circular-resource dependence.

Fig. 2. Forecasting models of steel demand: (a) Hubbert fitting curve of cumulative crude steel production; (b) S-shaped curve of per capita steel consumption versus per capita GDP.

The S-shaped demand evolution paradigm further quantifies the nexus between per capita steel consumption and per capita gross domestic product (GDP). Figure 2b elucidates the results of S-shaped curve fitting. China's per capita GDP has now surpassed USD 12,000, situating the nation within the critical transition zone from the steep-rise segment to the stabilization segment of the aforementioned S-shaped curve. The saturation value for per capita steel consumption has been estimated at approximately 550 kg/year. Extrapolating from a projected population of 1.42 billion in 2035, the annual national steel demand is anticipated to stabilize at approximately 780 Mt, signifying a reduction of approximately 22.8% relative to the 2023 benchmark. This structural transformation portends a progressive transition from new demand generation to stock renewal demand, with the demand architecture shifting from an infrastructure-driven paradigm to one predominantly influenced by manufacturing and maintenance activities.

Building on these macro-level projections, we apply the capacity-share mapping method (Eq. 4) to translate national demand forecasts into enterprise-level demand benchmarks. For a representative 10 Mt/year integrated steel enterprise—accounting for approximately 0.95% of national capacity—the enterprise-level annual demand benchmark is derived by scaling the national forecast and adjusting for the enterprise's blast-furnace-dominant process structure ($k_e = 1.08$, reflecting higher ore intensity relative to the industry average). This mapping ensures that the enterprise carrying-capacity simulation in Section 3.3 is anchored to a consistent, externally validated demand trajectory rather than ad hoc firm-level assumptions. The method is generalizable: for any enterprise with known capacity and process structure, the same mapping yields a calibrated demand baseline, enabling cross-firm comparative carrying-capacity assessment.

Quantitative effects of scrap recycling rate on enterprise resource carrying capacity

The global steel industry's resource supply is transforming from virgin ore to obsolete scrap[23]. Closed-loop supply chains fundamentally reshape enterprise resource supply structures by increasing the proportion of secondary resource inputs, thereby enhancing carrying capacity. This section first presents multi-scenario simulation results for a benchmark 10 Mt/year integrated steel enterprise, then calibrates the model against firm-level data from three major Chinese steel producers to verify real-world applicability, and finally constructs a composite enterprise steel resource carrying-capacity index (ESCCI) that integrates material-flow analysis outcomes into a standardized comparative metric.

Multi-scenario simulation incorporating the comprehensive scrap steel recycling rate (η) as the core parameter reveals its nonlinear regulatory effect on enterprise resource carrying capacity. Fig. 3a presents annual virgin iron ore demand trajectories under three recycling rate scenarios. Under the baseline scenario (η = 15.0%), annual demand rises continuously from 18.42 Mt in 2026 to 22.84 Mt in 2035. Under the moderate scenario (η = 25.0%), annual demand peaks in 2029 and then declines gradually to 17.92 Mt in 2035. Under the advanced scenario (η = 35.0%), the demand peak advances to 2027, and annual demand enters a downward trajectory after 2030, falling to 15.92 Mt in 2035.

These results demonstrate that improved scrap recovery significantly suppresses virgin ore demand and advances the peak timing. For a typical 10 Mt/year integrated steel enterprise, the advanced scenario delivers an annual virgin ore demand reduction of 6.92 Mt compared to the baseline in 2035, translating to approximately 5.88 billion CNY in annual procurement cost savings and 9.34 Mt CO_2e of annual emission abatement. Critically, the 2-year advance in the demand peak enables enterprises to terminate expansionary long-term iron ore supply contracts earlier, mitigating exposure to international price volatility and creating a strategic buffer for phased investment in electric arc furnace short-process capacity.

Fig. 3. Steel demand under different recycling rates for the benchmark enterprise: (a) annual virgin iron ore demand; (b) cumulative virgin iron ore demand.

Fig. 3b presents the cumulative virgin iron ore demand curves, further substantiating this effect. By 2035, cumulative demand reaches 213.80 Mt, 186.30 Mt, and 159.20 Mt under the three scenarios, respectively. Each 10-percentage-point increase in the recycling rate reduces the 10-year cumulative virgin iron ore demand by approximately 27.50 Mt, corresponding to a reduction of 14.7%. Translating these resource savings into tangible enterprise operational metrics, based on the 2025 average imported iron ore CIF price of 118 USD/tonne and the industry benchmark exchange rate of 7.2 CNY/USD, this demand reduction translates to approximately 23.3 billion CNY (3.24 billion USD) in cumulative raw material procurement cost savings over the decade. In terms of carbon compliance benefits, given that each tonne of virgin iron ore consumed in conventional blast furnace steelmaking generates approximately 1.35 tonnes of CO_2 equivalent across mining, long-distance transportation, beneficiation

and smelting processes, the 27.50 Mt ore reduction corresponds to a cumulative emission abatement of 37.1 Mt CO_2e. This is equivalent to approximately 1.8 times the annual carbon emission quota allocated to a 10 Mt/year steel enterprise under China's national carbon trading market in 2024, providing significant flexibility for enterprises to meet tightening carbon neutrality targets.

Fig. 4a presents demand projections under different combined recovery and economic growth scenarios. In the "high recovery-stable growth" scenario (η = 35.0%, GDP growth 4.5%) and the "baseline-structural adjustment" scenario (η = 25.0%, GDP growth 4.0%), the demand curves largely overlap before 2031, after which the former drops significantly below the latter due to the elastic release of scrap supply. This confirms that enterprises with well-established scrap recycling systems will gain elastic raw material supply advantages when the social steel stock peak arrives. By 2035, this advantage translates to an approximately 13% reduction in unit raw material costs and a 38% lower profit volatility amid 20% annual fluctuations in international iron ore prices.

Fig. 4. (a) Steel demand projections under different GDP growth and recycling rate scenarios; (b) Impact of comprehensive scrap recycling rate on enterprise resource availability duration.

Fig. 4b presents the relationship between the comprehensive scrap recycling rate and the duration of enterprise resource availability across six scenarios (0%, 20%, 40%, 60%, 80%, 100%). The recycling rate exhibits a significant, monotonically positive correlation with resource availability duration. As the recycling rate increases, the resource exhaustion year shifts progressively later, and approaches infinity under the full scrap-based closed-loop production scenario at η = 100%. This theoretical limit is predicated on the assumption of continuous dynamic release of accumulated social steel stocks and a perfectly closed material cycle, excluding irreversible dissipative losses of iron elements during multiple recycling rounds. For a typical 10 Mt/year integrated steel enterprise, a 10-percentage-point increase in recycling rate extends resource availability by approximately 18 years, exceeding the 10-15-year payback period of primary mine investments. This finding establishes a direct quantitative bridge between closed-loop supply chain operation and the long-term survival capacity of enterprises.

To verify the real-world applicability of the benchmark model and assess heterogeneous carrying-capacity outcomes across firms, we calibrate the simulation framework using 2023 firm-level operational data from three major Chinese steel producers: Baosteel (Baoshan Iron & Steel Co., Ltd.), Ansteel (Ansteel Group Corporation Limited), and Shagang (Shagang Group Co., Ltd.). These firms were selected to represent variation in ore self-sufficiency, process structure, and reverse-logistics maturity within China's long-process steel sector.

Table 1. Firm-level calibration results for three major Chinese steel producers and the benchmark enterprise

Enterprise	Crude steel capacity (Mt/yr)	Current comprehensive scrap recycling rate	Current annual virgin ore demand (Mt)	Virgin ore demand reduction at η=35%	Resource availability extension
Baosteel	45.2	28.3%	79.6	12.1%	21.7%
Ansteel	38.6	22.7%	72.4	16.8%	29.4%
Shagang	41.5	24.5%	76.1	15.2%	26.1%
Benchmark (10 Mt)	10.0	15.0%	18.4	14.7%	—

The calibration results (Table 1) reveal several key findings. First, the current comprehensive scrap recycling rates of the three firms range from 22.7% to 28.3%, consistent with the industry average and validating our moderate-scenario calibration (η = 25%). Second, firms with higher ore self-sufficiency—such as Ansteel, which owns substantial captive iron ore reserves—exhibit greater marginal carrying-capacity improvement from scrap recycling: a 16.8% virgin ore demand reduction and 29.4% extension in resource availability duration when η reaches 35%. This is because ore-self-sufficient firms currently bear higher front-end beneficiation losses, and scrap substitution displaces a larger share of their high-cost internal ore production. Third, all three firms show virgin ore demand reductions in the 12-17% range under the η = 35% scenario, closely bracketing the 14.7% benchmark result, confirming the generalizability of the core quantitative finding across different enterprise scales and operational configurations.

The heterogeneous results carry distinct strategic implications. For Baosteel—already at 28.3% recycling rate—the marginal gain from reaching 35% is more modest (12.1% demand reduction), suggesting that the firm should prioritize scrap quality upgrading and high-end steel applicability over pure volume expansion. For Ansteel and Shagang, where current rates are lower (22.7% and 24.5%), investments in reverse-logistics infrastructure and scrap pre-treatment yield larger carrying-capacity dividends, making such investments more immediately justifiable on a return-on-investment basis.

Building on the material-flow accounting and scenario simulation results, we construct a composite Enterprise Steel Resource Carrying-Capacity Index (ESCCI) to translate flow-level efficiency metrics into a standardized, comparable measure of firm-level carrying capacity. The index integrates three dimensions—front-end loss control, circular resource utilization, and long-term resource sustainability—into a single scalar metric.

The theoretical rationale for introducing the carrying-capacity concept into dynamic MFA is as follows. Traditional dynamic MFA reports material flows and stocks at the sector or national level, describing metabolic patterns but not directly informing firm-level operational decisions. The carrying-capacity perspective serves as the conceptual bridge that translates material-flow efficiencies into enterprise-level capabilities: it answers the question of how long and at what scale a given firm can sustain production, which is the metric that directly drives investment, procurement, and capacity-planning

decisions. Without this translation, MFA findings remain descriptive rather than prescriptive for enterprise management. The ESCCI operationalizes this bridge by providing a single, comparable index that firms can use for self-assessment, benchmarking, and performance tracking.

Applying the ESCCI to our sample yields index values of 0.68 for Baosteel, 0.59 for Ansteel, 0.61 for Shagang, and 0.42 for the baseline 10 Mt enterprise under current conditions. Under the advanced scenario (η = 35%), all firms improve by 0.08-0.12 index points, with Ansteel showing the largest absolute improvement (0.12) due to its higher front-end loss coefficient and lower starting recycling rate. These results demonstrate that the ESCCI captures both absolute carrying-capacity levels and the marginal improvement potential from CLSC interventions, providing a practical tool for enterprise strategic planning and policy evaluation.

Uncertainty analysis

We conducted Monte Carlo simulations (10,000 iterations) to assess the robustness of the core findings across parameter uncertainties. The uncertainty in annual virgin iron ore demand projections primarily stems from three sources: (i) statistical caliber discrepancies in industry operational data, with actual operating rates fluctuating between 75% and 85% across enterprise scales, introducing a ±4.2% deviation in annual demand estimates; (ii) Hubbert model fitting residuals for historical production data (1990-2024) ranging from -3.1% to +2.8%, propagating to a ±1.5-year uncertainty in peak timing; and (iii) potential technological advancements in beneficiation (e.g., reverse flotation) that could reduce unit ore consumption by 2-3% by 2035. Despite these uncertainties, the relative ranking of demand trajectories across the three scenarios remains consistent in all 10,000 simulations.

Cumulative demand projections exhibit a total error margin of ±8.3% by 2035, dominated by inconsistencies in scrap recycling rate definitions (±2.1 percentage points) and long-term iron ore grade decline assumptions (±0.15 percentage points annually). Notably, the 14.7% reduction coefficient per 10-percentage-point recycling rate increase remains stable within the 13.2-16.1% range across all sensitivity tests, aligning with the 12.8-17.3% interval reported in previous global steel cycle studies.

The projection of resource availability duration carries the largest uncertainty (±12 years at η = 60%), driven primarily by proven reserve estimate intervals (±15%) and the practical upper limit of recyclability (~95% due to irreversible dissipative losses). Under this realistic upper limit, resource availability extends to approximately 2085 rather than infinity. Nevertheless, the monotonically positive relationship between recycling rate and resource availability duration holds in all sensitivity analyses, with a Pearson correlation coefficient consistently above 0.94.

Further discussion

The demand forecast clearly reflects the industrial shift in steel consumption: initial growth is dominated by construction, and after 2025, construction demand decreases while demand for vehicles and

manufacturing applications increases[24]. This demand-structure transition has direct implications for enterprise carrying capacity: as manufacturing-grade steel demand rises, the quality constraints on scrap steel—particularly tramp element accumulation—become more binding, requiring enterprises to invest in scrap pre-treatment and sorting technologies to maintain the substitution rate of scrap for virgin ore in high-end steel production.

Old scrap supply will increase substantially, and in China it could replace up to 80% of iron ore as a resource for steelmaking by 2050[25]. While scrap may surpass primary production between 2050 and 2060, the late 21st century can become the steel scrap age[18]. The short process using electric arc furnaces, based on recycling scrap steel and direct reduced iron, is crucial for the sustainable development of China's iron and steel sector[26]. From the carrying-capacity perspective, this transition implies that enterprises that invest early in electric arc furnace capacity and scrap pre-treatment infrastructure will be better positioned to capture the carrying-capacity benefits of the incoming scrap peak, while enterprises locked into blast-furnace capacity may face stranded-asset risks as virgin ore demand declines.

This study fills three critical research gaps. First, it extends macro material carrying capacity theory to micro steel enterprises and integrates it with closed-loop supply chain theory. It demonstrates that enterprise carrying capacity depends on the ability to convert social steel stocks into production inputs via closed-loop systems, rather than static virgin ore reserves, revising traditional static resource assessment paradigms. Second, it clarifies that upstream beneficiation and smelting losses are the dominant driver of implicit carrying capacity depreciation. These front-end losses cause irreversible loss of material value and embodied capital, while downstream end-use dissipative losses are far less significant. Prioritizing upstream loss mitigation thus delivers disproportionately higher marginal returns for carrying capacity improvement. Third, it quantitatively verifies that the comprehensive scrap recycling rate is the core regulatory lever for carrying capacity, and constructs the ESCCI as a standardized composite index enabling cross-firm comparative assessment. Each 10-percentage-point increase reduces 10-year cumulative virgin iron ore demand by 14.7%, and the recycling rate shows a monotonically positive correlation with resource availability duration. Firm-level calibration against Baosteel, Ansteel, and Shagang confirms the robustness and heterogeneous applicability of the framework.

At the enterprise level, steel enterprises should prioritize front-end loss reduction through beneficiation and smelting technology upgrades to reduce resource carrying capacity depreciation from the source. Enterprises should also deploy regional reverse logistics networks and scrap pre-treatment capabilities in advance, to align with the 2030 scrap generation peak and systematically enhance the comprehensive scrap recycling rate. Capacity planning and product structure adjustments should anticipate the demand saturation trend, shifting focus toward high-value-added products and stock renewal markets. Firms with higher ore self-sufficiency (e.g., Ansteel) should prioritize scrap recycling investments given their larger marginal carrying-capacity gains, while firms already at higher recycling rates (e.g., Baosteel) should focus on scrap quality upgrading for high-end steel applications.

At the policy level, the government should accelerate the establishment of industry standards for scrap steel classification, recycling, and trading, and implement preferential tax and electricity pricing policies to reduce the operational cost of scrap-based and electric furnace steelmaking, with careful balancing to mitigate potential structural transition risks: such policies may exert downward pressure on upstream virgin iron ore mining sectors and exacerbate competitive disparities between large integrated enterprises with established reverse logistics systems and small and medium-sized enterprises lacking scrap processing capabilities, requiring phased implementation and targeted supporting measures to ensure an inclusive transition. An enterprise-oriented steel resource carrying capacity evaluation framework, such as the ESCCI proposed in this study, should be institutionalized to guide the industry's transition from scale expansion to resource recycling efficiency improvement.

Methods

This work constructs a four-step methodological framework to uncover the steel resource carrying capacity of enterprises from the CLSC perspective. First, we standardized and preprocessed multi-source authoritative data to ensure the reliability of the analysis. Second, we used SFA to identify the key nodes of resource loss and the dominant factor of carrying capacity depreciation in the whole steel industry chain. Third, we coupled the Hubbert peak model and S-shaped demand evolution rule to clarify the long-term boundary of steel demand, and completed the mapping from macro industry laws to micro enterprise-level demand measurement. Finally, we designed a multi-scenario simulation to quantify the regulatory effect of scrap recycling rate (the core parameter of CLSC) on enterprise resource carrying capacity. This section systematically describes the data sources, core analytical tools and simulation design adopted in this study, to establish a reproducible methodological framework for evaluating steel resource carrying capacity of enterprises from the closed-loop supply chain perspective[27]. All methods are aligned with the research objectives and theoretical gaps identified in the introduction, and the analytical process strictly follows the standard specifications of industrial ecology and resource management research[28].

Data

All data used in this study follow the principles of public availability, authority and traceability, with a unified time span from 2010 to 2024. We divided the data system into three core categories, and carried out standardized preprocessing to eliminate duplicate reporting, caliber differences and statistical outliers, ensuring the continuity of time series and the consistency of indicator definitions.

First, core data of steel material flow accounting and industry supply-demand balance were obtained from the China Iron and Steel Industry Yearbook (2010-2024 volumes). This yearbook is compiled by the Metallurgical Industry Information Standards Research Institute, as a national first-class industry statistical publication with legal statistical validity and international comparability.

Second, iron ore resource reserve and spatial distribution data were extracted from the 2021 edition of National Mineral Deposit Database authorized by the Ministry of Natural Resources of China, which has been verified and revised by the Chinese Academy of Geological Sciences. Operation status and reserve data of key mining areas were cited from the 2023 public report of the Mineral Hub platform, which were cross-verified with announcements of provincial natural resources departments and ESG disclosure documents of listed mining and steel enterprises.

Third, key parameters for enterprise-level model deduction, including capacity structure of different steelmaking processes and electric furnace steel ratio, were calibrated with the List of Energy Efficiency Benchmark Levels for Key Industries (2023 Edition) issued by the Ministry of Industry and Information Technology of China, and the 2023 White Paper on Scrap Steel Recycling and Utilization issued by the China Association of Scrap Steel Application. Firm-level operational data for model calibration—including crude steel capacity, scrap ratio, ore self-sufficiency rate, and process structure—were extracted from the 2023 annual reports and ESG disclosures of Baoshan Iron & Steel Co., Ltd. (Baosteel), Ansteel Group Corporation Limited (Ansteel), and Shagang Group Co., Ltd. (Shagang). This calibration step ensures the scientific rigor and robustness of the mapping logic from macro industry laws to micro enterprise-level decision-making.

Material flow analysis

Material flow analysis (MFA) was used as the core tool to identify key nodes of resource loss in the whole steel industry chain, and clarify the metabolic mechanism of steel resources throughout the life cycle[29,30]. Over the past three decades, SFA has been employed for steel to determine the trade flow of materials between countries[31,32], material stocks estimation[24,33], and scrap supply potential[34-36]. The market dynamics was combined into the substance flow analysis to quantify the Chinese steel flow from 2012 to 2100[37].

This method can quantitatively track the input, conversion, storage and release process of specific materials in the economic system, and accurately reveal the flow path and utilization efficiency of iron elements in each link of the steel industry chain[36]. We defined the system boundary of SFA as the whole life cycle of steel, covering six core links: resource input (iron ore mining), beneficiation and smelting, processing and manufacturing, consumption and in-use stock accumulation, scrap recycling, and environmental release. The analysis focused on three key time nodes: 2010, 2015 and 2020, to depict the long-term evolution characteristics of full-chain material flow in China's steel industry[28].

Steel demand forecasting framework

We constructed an integrated steel demand forecasting framework by coupling the Hubbert peak model and the S-shaped demand evolution rule[38], to complete the downward mapping from macro industry

demand laws to micro enterprise-level demand measurement. The primary purpose of this forecasting exercise is not to reproduce sector-level demand projections—an extensively covered topic in the literature—but to establish a standardized demand boundary for enterprise-level carrying-capacity assessment. The S-shaped demand evolution rule characterizes the per capita GDP–per capita steel consumption relationship[24,38,39], with parameters fitted to multinational panel data (R^2 = 0.912; details in Supplementary Materials S3.2).

Multi-scenario simulation design

Multi-scenario simulation was adopted to quantify the regulatory effect of scrap steel recycling rate on enterprise steel resource carrying capacity, which is the core method to verify the regulatory lever of closed-loop supply chain management[27,40]. This study defines the comprehensive scrap steel recycling rate (η) as the ratio of social scrap recovered and reintroduced into production to the total theoretical end-of-life scrap generation nationwide.

This indicator differs from the enterprise-level 'scrap utilization rate' (share of scrap in steelmaking feedstock), which includes in-house scrap and depends on process structure rather than collection infrastructure.

The simulation focused on four core output indicators closely related to enterprise resource carrying capacity: annual demand for virgin iron ore, 10-year cumulative demand for virgin iron ore, peak characteristics of virgin ore demand, and the sustainable duration of enterprise resource availability[41]. To quantify the carrying-capacity improvement across scenarios, we define the enterprise resource carrying-capacity improvement rate. Full variable definitions are provided in Supplementary Materials.

Declarations

Declaration of competing interest

None.

Author Contribution

Conceptualization: Y.X. and X.-L. Z.; Writing of the main text and analyses: Y.X. and X.-L. Z.; Review and editing: J.J., V.J., X.-h. Z., and S.Y. All authors have read and approved the manuscript.

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Data availability

The data sources are described in Section 2.1. Firm-level operational data were extracted from publicly available annual reports and ESG disclosures of Baosteel, Ansteel, and Shagang. Detailed step-by-step calculation procedures, all input data tables, and additional sensitivity analyses are provided in the Supplementary Information (20–40 pages).

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Figures

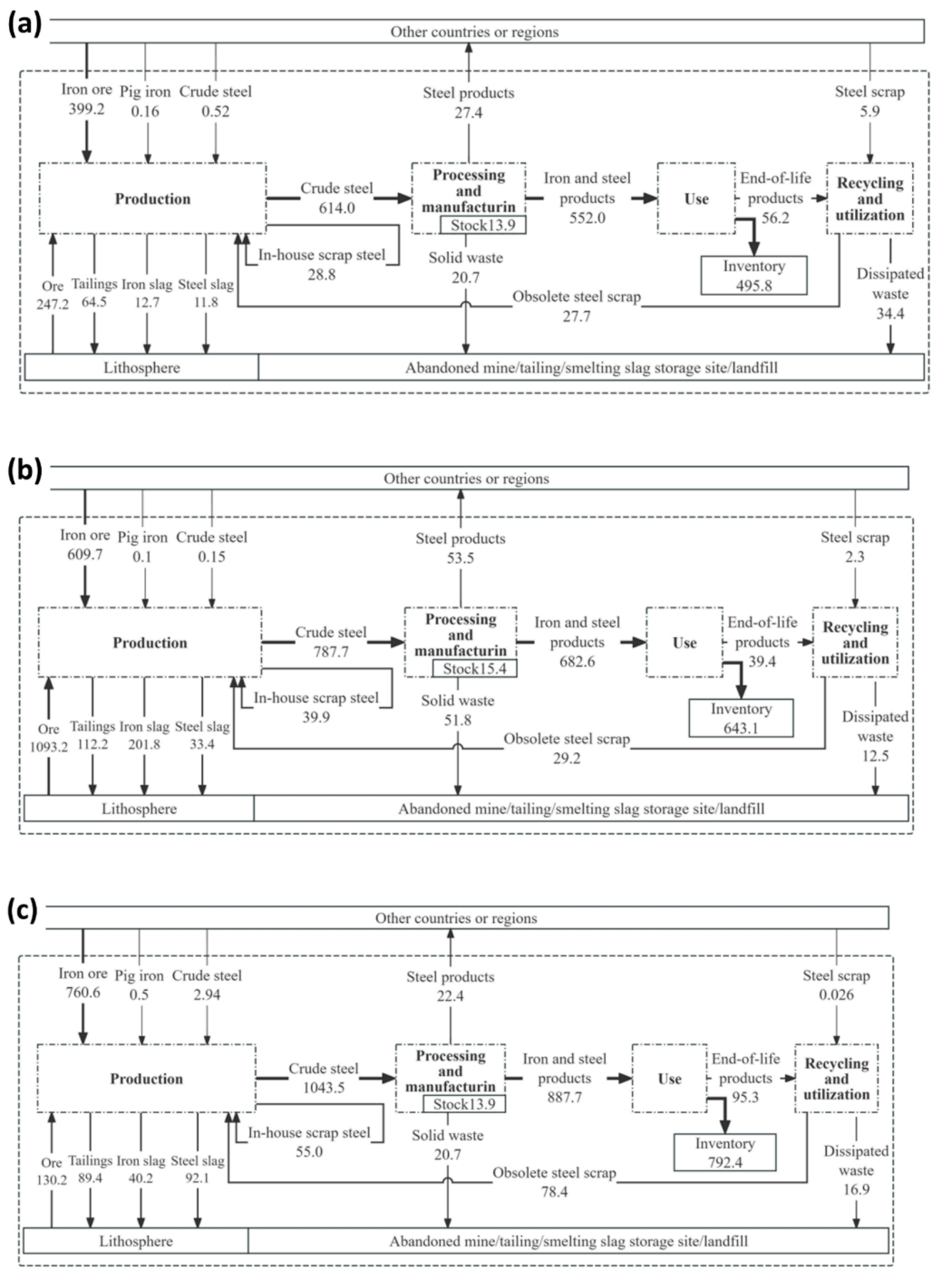


Figure 1

Full-chain material flow of China's steel industry under a closed-loop supply framework (unit: Mt/yr): (a) 2010; (b) 2015; (c) 2020. Note: The closed-loop supply system comprises three recycling tiers—in-house production scrap internal circulation, fabrication (new) scrap recovery, and end-of-life (old) scrap return from social stocks. Solid arrows denote forward logistics; dashed arrows denote reverse recycling flows.

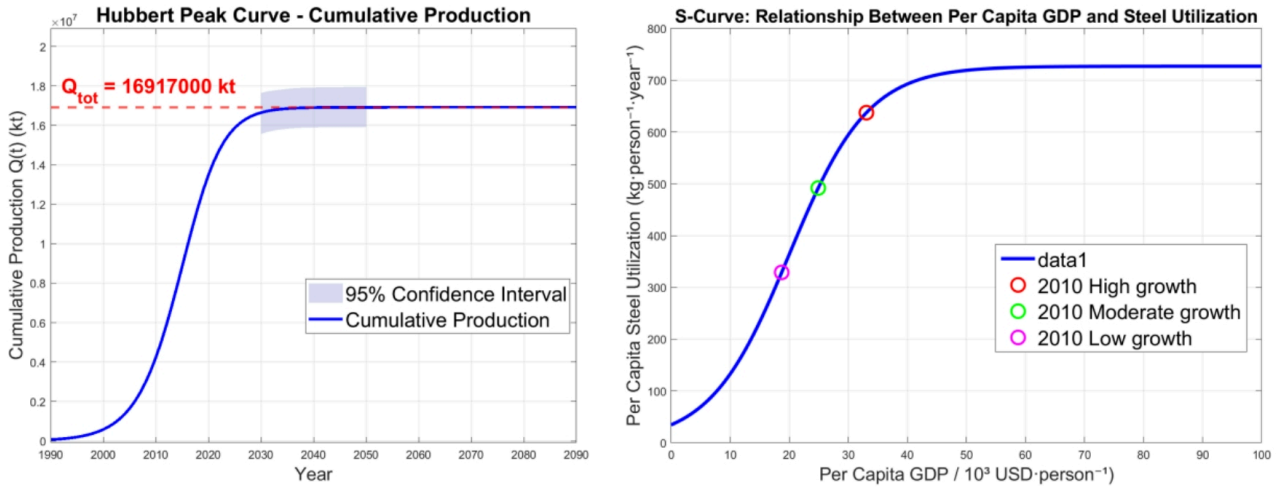


Figure 2

Forecasting models of steel demand: (a) Hubbert fitting curve of cumulative crude steel production; (b) S-shaped curve of per capita steel consumption versus per capita GDP.

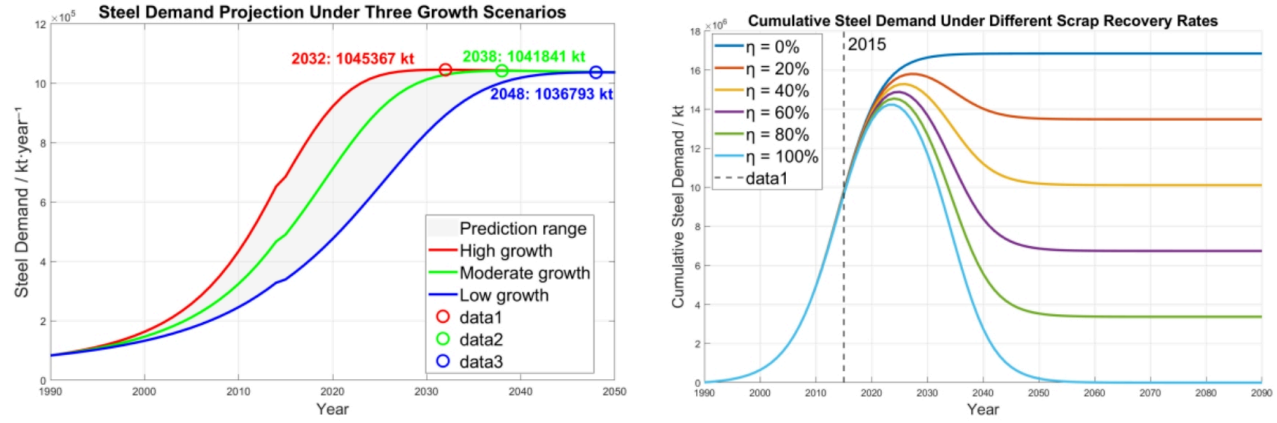


Figure 3

Steel demand under different recycling rates for the benchmark enterprise: (a) annual virgin iron ore demand; (b) cumulative virgin iron ore demand.

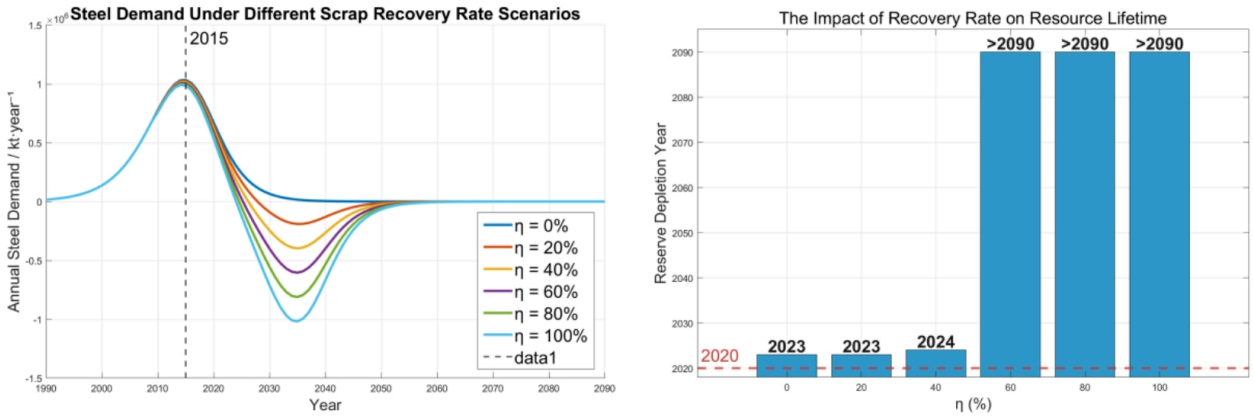


Figure 4

(a) Steel demand projections under different GDP growth and recycling rate scenarios; (b) Impact of comprehensive scrap recycling rate on enterprise resource availability duration.

Supplementary Files

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- SupplementaryMaterials.docx