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The Steel Scrap Age

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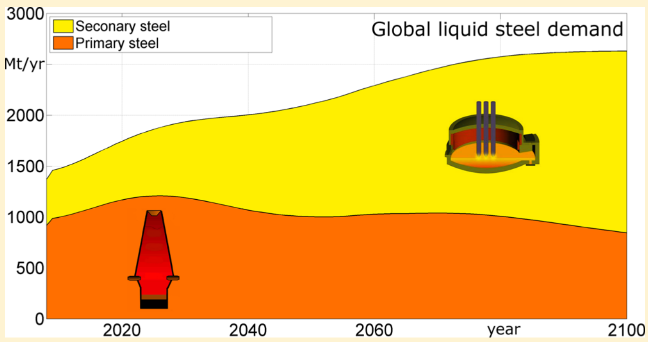
Supporting Information

ABSTRACT: Steel production accounts for 25% of industrial carbon emissions. Long-term forecasts of steel demand and scrap supply are needed to develop strategies for how the steel industry could respond to industrialization and urbanization in the developing world while simultaneously reducing its environmental impact, and in particular, its carbon footprint. We developed a dynamic stock model to estimate future final demand for steel and the available scrap for 10 world regions. Based on evidence from developed countries, we assumed that per capita in-use stocks will saturate eventually. We determined the response of the entire steel cycle to stock saturation, in particular the future split between primary and secondary steel production.



During the 21st century, steel demand may peak in the developed world, China, the Middle East, Latin America, and India. As China completes its industrialization, global primary steel production may peak between 2020 and 2030 and decline thereafter. We developed a capacity model to show how extensive trade of finished steel could prolong the lifetime of the Chinese steelmaking assets. Secondary steel production will more than double by 2050, and it may surpass primary production between 2050 and 2060: the late 21st century can become the steel scrap age.

INTRODUCTION

Steel production accounts for ca. 25% of industrial and 9% of anthropogenic energy- and process-related greenhouse gas emissions.[1] The production level is not limited by resource availability: Iron ore and coal are abundant and spread over many countries,[2] secondary production is well established, and end-of-life recovery rates are high.[3] Climate change mitigation, however, may represent a major constraint to future production growth.[4] To develop roadmaps for substantial emissions reduction within the steel sector, stakeholders and policy makers need information on trends in steel use, steel demand, and the amount of scrap which is available for recycling in different world regions. This knowledge is crucial when deciding where to locate new production facilities and whether to invest in primary or secondary production. It forms the basis for estimating the future sectoral carbon footprint.

Long-term forecasts on global steel demand until 2030 and beyond have been published by both international institutions[5−7] and several scholars.[8,9] All approaches, except Hatayama et al.,[9] extrapolate recent growths rates in steel consumption,[8] or rely on exogenous GDP projections and a function coupling GDP to steel consumption, as in the World Energy Model[5] and the steel module of the POLES model.[7]

Steel-containing products provide service over several decades[10] and hence, the *in-use stock* of steel rather than the *consumption flow* is a more adequate service measure. Steel consumption is only a means to build up or maintain in-use stocks, and the latter provide the actual service to society. By extrapolating steel consumption trends one ignores the dynamics of the in-use stocks and one can therefore neither connect consumption to the actual service provided, nor estimate the future supply of post consumer scrap from products leaving the stock at the end of their lifetime.[11] Instead, availability of postconsumer scrap is often taken for granted.

Steel demand and scrap supply have been forecast based on assumptions on future stock development and product lifetime both on the country[12] and on the global scale:

Hatayama et al.[9] use a stock-driven model to estimate global steel demand until 2050 and track three end-use categories in eight world regions: buildings, civil engineering (infrastructure), and passenger vehicles. Their work covers about 85% of the steel stock in developed countries, but it includes only the use phase of steel and does not investigate how the steel industry and waste management could respond to steel demand and scrap supply. Since most carbon emissions associated with steel occur in the production phase and vary greatly between primary and secondary production,[6] modeling the entire steel cycle is an important step toward envisioning the future structure of the

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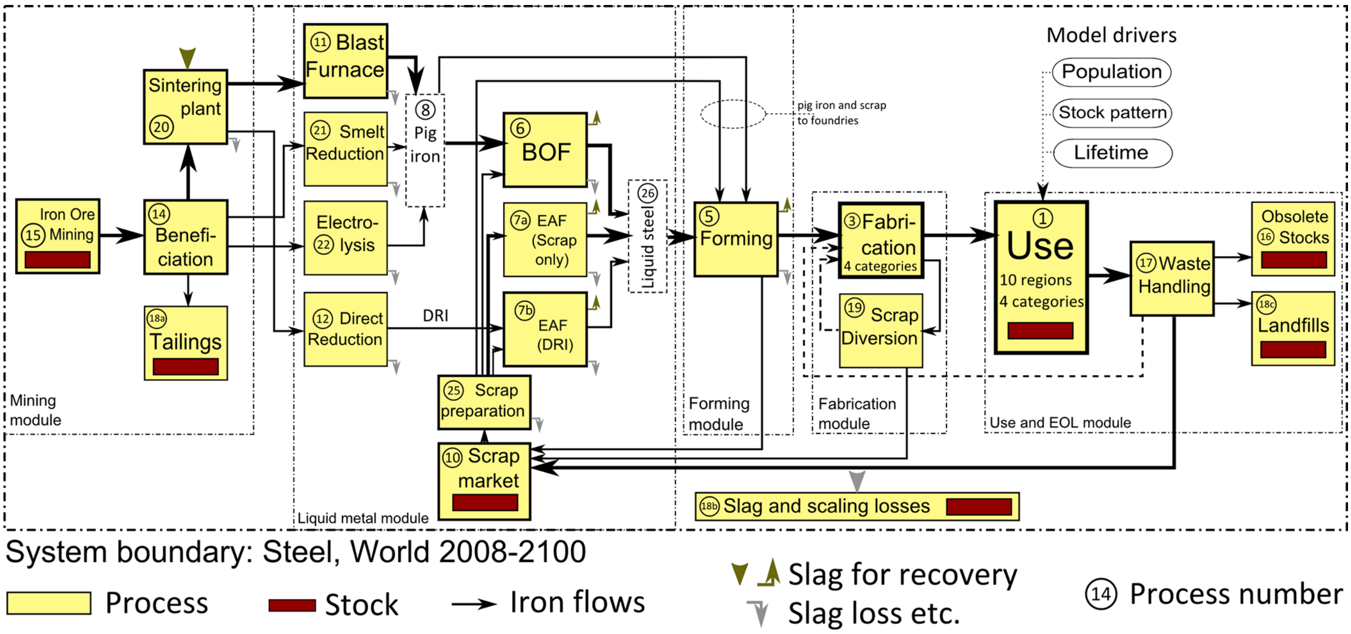

Figure 1. System definition. BOF = basic oxygen furnace, EAF = electric arc furnace, DRI = direct reduced iron.

steel industry and creating mass-balance consistent long-term scenarios on climate change mitigation within the sector.

In the OECD countries, per capita in-use stocks of steel are between 6 and 16 tonnes.[10,11] Per capita stocks in several developed countries have leveled out in the range of 14 ± 2 tonnes, and another group of ca. 10 countries with stocks between 10 and 14 tonnes shows signs of saturation in the same range.[10] This phenomenon can be explained by the completion of urbanization and infrastructure development and the subsequent transition to a less steel-intensive service-based economy.[11] In previous work[12] we built scenarios for the Chinese steel cycle assuming stock saturation, and found a peak in steel demand that is insensitive to significant changes of both saturation level and lifetime. Once steel stocks in China will reach the stock levels of other industrialized countries, they may saturate, demand may plummet, and a new *steel crisis*[13] may occur.

In the article at hand, we extend our work on China to global coverage and examine the consequence of a worldwide future saturation of per capita in-use stocks of steel on material flows in the entire steel cycle. We address the following questions:

(1) What trends in regional steel demand and scrap supply follow from a saturation of per capita stocks everywhere in the world? When and where may peaks in steel demand occur?

(2) What are likely future challenges for producers of both primary and secondary steel and how could steel producers and the waste management industry respond to them?

In the connected article,[14] Milford et al. extend the work presented here by including CO_2 emissions and by studying the potential contribution of energy and material efficiency to a substantial reduction of sectoral carbon emissions by 2050.

■ MATERIALS AND METHODS

To answer the questions above we performed a material flow analysis of the entire steel cycle, which covered mining, primary and secondary steel production, fabrication, use, and waste management (Figure 1). The complete system definition, the model approach, all data sources and the data treatment are covered in the Supporting Information (SI). Historic time series of steel stocks in industrialized countries[10,11] show that once steel stocks have reached a certain level, steel use may decouple from economic development. We based our scenarios on the hypothesis that *eventually, all world regions will benefit from the same services provided by steel stocks as industrialized countries do today*. For this article we assumed that service level is coupled to stock level and that all world regions will follow the stock pattern of the developed countries with the most mature steel stocks. In the connected paper we explored how service level and material use can be decoupled.[14]

The total regional in-use stocks are determined by multiplying population forecasts with the respective per capita stock pattern. There are two ways of connecting final demand, stocks, and discards with each other: For the period 1700–2008, the apparent final steel consumption was compiled in previous work[10] and a lifetime model was used to determine the fraction of final consumption that has already left the in-use stock.[15] For the years 2009–2100, we needed an inverse approach to determine the inflow from a given per capita stock trajectory: In a year-by-year calculation, we first determined the annual discards from past consumption using the lifetime model, and then final steel demand from mass balance (eq 1):

$$\text{final demand} = \text{inflow} = \text{outflow} + \text{stock change} \qquad (1)$$

All processes except the use phase were characterized by transfer coefficients that may change over time, such as the yield loss rate in fabrication or the share of scrap used in basic oxygen furnaces. The output of these processes was determined by a linear model, which contains all transfer coefficients quantified by Cullen et al.,[16] with final steel demand and total discards as exogenous drivers. The split between primary and secondary steelmaking was chosen so that all recovered scrap was recycled.

Below we explain our choices for the geographic resolution, the time frame, and the model drivers.

Table 1. Saturation Level by Category and Region; Saturation Time

	region	transportation		machinery		construction		products		total stock (tonnes)	saturation time (t_S)
		saturation level (tonnes) and lifetime (years)									
1	North America	1.5	20	1.6	30	9.5	75	0.7	15	13.3	2020
2	Latin America	1.5	20	1.6	30	10	75	0.6	15	13.7	2100
3	W. Europe	1.3	20	0.9	30	10	75	0.6	15	12.8	2030
4	Former USSR	1.5	20	0.9	30	10	75	0.4	15	12.8	2030
5	Africa	1.5	20	1.6	30	10	75	0.6	15	13.7	2150
6	Middle East	1.5	20	1.6	30	10	75	0.6	15	13.7	2100
7	India	1.5	20	1.6	30	10	75	0.6	15	13.7	2150
8	China	1.5	20	1.6	30	10	75	0.6	15	13.7	2050
9	developed Asia	1	13.3	1.6	20	12	50	0.8	10	15.4	2020
10	developing Asia	1.5	20	1.6	30	10	75	0.6	15	13.7	2150

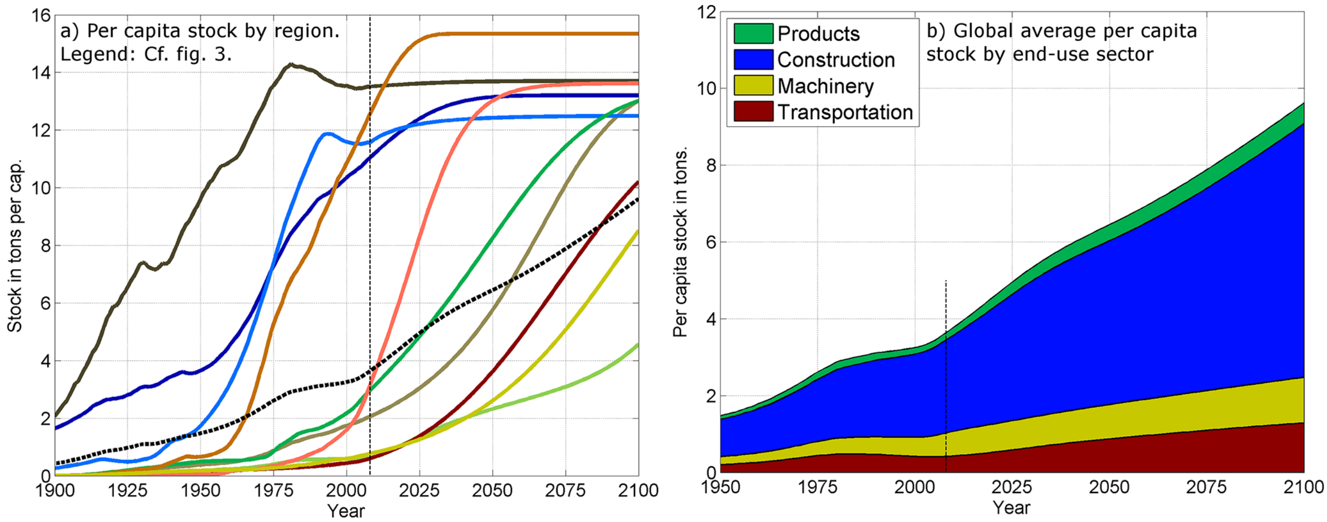

Figure 2. Assumptions on future stock patterns and resulting average global stock by end use sector.

Geographic Scale. Country-specific forecasts require an accurate assessment of existing stocks and country-specific assumptions on future stock development. This approach is limited by the available data on steel end use and product lifetime. A global model could not reflect the differences between industrialized countries and the developing world. As a compromise, we considered 10 world regions, each comprising countries at a similar stage of economic development: North America, Latin America, Western Europe, Commonwealth of Independent States (CIS), Africa, Middle East, India, China, Developed Asia and Oceania, and Developing Asia. Only the use phase was modeled on the regional level; for all other processes we aggregated flows to the global scale due to the high level of international steel trade and because there is a global market for steelmaking technology.

Time Horizon. Much of the steel produced goes into buildings and infrastructure, which have a lifetime of many decades or even centuries.[17] The long economic lifetime of steelmaking assets also requires a time horizon of at least 60 years (SI S2.8). In contrast, climate change mitigation requires significant efforts within the next few decades. We chose to model production, use, and recycling in the steel cycle until 2100, and set 2050 as target year for the scenarios on energy consumption, material efficiency, and emissions explored in the connected paper.[14]

End-Use Sectors. Material quality requirements and lifetime vary greatly between buildings, cars, machines, laptops, and other steel-containing products. There are no standard end-use categories used in steel statistics, and we used the four sectors: construction, transport, industrial equipment (machinery), and metal products and containers, as a compromise between aggregation and accuracy.

Per Capita Stock Trajectory. The time t_S when the stock reaches 99% of the assumed saturation level is coupled to other factors, especially economic development.[11] One could try to infer the saturation time from exogenous GDP projections, but this would merely represent a shift from one exogenous parameter to another and would also raise the issue of interdependency of population estimates and GDP projections. We therefore chose to enter the saturation time directly into the model. In previous studies a three-parameter logistic growth curve was used to model future per capita stock.[9,12] After fitting the curve to the latest stock value and its growth rate, only one free parameter remains, which can be either the saturation level $\hat{S}$ or the saturation time t_S. In order to choose saturation level and time independently for the different regions, we needed to add one parameter to the stock curve. We developed the following generalized logistic curve, which is a synthesis of the logistic curve and the Gompertz model, both of which are commonly used to model saturation phenomena (eq 2):[18]

$$S(t) = \frac{\hat{S}}{1 + \left(\frac{\hat{S}}{S_0} - 1\right)\cdot \exp(c\cdot(1 - \exp(d\cdot(t - t_0))))} \quad (2)$$

The parameters are: t: time, $\hat{S}$: saturation level, S_0: stock at a given t_0. c and d are two shape parameters that are chosen numerically so that two further boundary conditions hold: (i) the model curve is tangential to the historic curve in $t_0 = 2008$ and (ii) the stock reaches 99% of the saturation level at a given t_S.

Parameter Choice. The baseline scenario comprises population estimates used in the IPCC AR3;[19] our best estimates of stock saturation levels and lifetimes[10] (Table 1); a gradual improvement of end-of-life recovery rates, estimated by WorldSteel;[3] and the assumption that for each year, all recovered scrap is fed back into steelmaking. According to historic evidence[10] we assumed the following per capita saturation levels: transportation (1.5 tonnes), machinery (1.6 tonnes), construction (10 tonnes), and products (0.6 tonnes) (Table 1). The saturation levels for the developed regions needed to be adapted slightly to better fit the individual historic development (Figure 2a). Steel stocks in China have been estimated to saturate around 2050,[12] and we assumed that Latin America and the Middle East will follow 50 years later, while saturation on the global scale was assumed to happen around 2150.

Figure 2a shows the stock model curves resulting from inserting the parameter choices in Table 1 into eq 2. Global average per capita stock will grow from the present 3.7 tons to ca. 6.5 tons in 2050, and to ca. 10 tons in 2100 (Figure 2b). Construction accounts for 75% of the stocks, followed by transportation (ca. 10%) and machinery (ca. 8%). Around 2060, the global average per capita stock will reach 50% of the saturation level of industrialized countries.

Future Primary Steel Production by Region. To explore future utilization of primary production facilities, we developed a demand-driven capacity model that tracks the different blast furnace cohorts in the different regions over time. After analyzing historic blast furnace statistics, we found that the physical lifetime of blast furnaces is typically 60−100 years.[20]

In times of increasing demand the average overcapacity margin is around 8%,[21] and when demand stalls, overcapacities are demolished after a waiting period that we assume to be five years, beginning with the oldest assets. Facilities that reach a lifetime of 100 years are taken out of use for technical reasons and replaced by new capacity if there is sufficient demand. We considered decommissioning before reaching a lifetime of 60 years as uneconomic (SI S2.8). For the years until 2008, the age structure of the primary steel sector was determined using historic regional pig iron production figures.[10]

For the future primary production capacity development we considered two cases: (i) In the globalized case—”trade follows capacity”—we assumed that production is allocated to existing assets, independent of where demand occurs, and the finished steel is shipped to where it is needed. (ii) In the regional approach—”capacity follows demand”—we assumed that different world regions build up their own capacity as they develop, for example, due to concerns about resource security and independency, irrespective of whether there is steel production capacity available elsewhere.

A detailed description of the capacity model is given in section S2.8 in the Supporting Information.

RESULTS

The faster the stock reaches saturation, the more drastically final steel demand drops after peaking in the years of fastest stock growth (Figure 3a): China shows a pronounced peak at ca. 550 Mt/yr around 2020, followed by smaller peaks in the Middle East around 2050 (ca. 150 Mt/yr) and India (ca. 400 Mt/yr), Latin America (ca. 300 Mt/yr), and Developing Asia (ca. 280 Mt/yr) between 2070 and 2090. Saturation of per capita stock, in combination with a growing population, leads to a slightly increasing demand for North America; in combination with a shrinking population, it leads to an almost 50% decrease in demand for Europe by 2100. The upward trend in steel demand in China in the late 21st century is a direct result of our lifetime assumptions: The high present construction demand together with the assumption of a mean lifetime of 75 years lead to a large “replacement wave” after ca. 2070.

Regional scrap flows change less rapidly (Figure 3b): While today, most scrap is sourced in the developed world, this will change after ca. 2025, when China will become the largest supplier of old scrap. By the end of the century, both steel consumption and scrap supply will be dominated by what today is the developing world.

We now look at steel demand and scrap supply on the global scale (Figure 4).

Aggregated final demand will increase from 1100 Mt/yr in 2008 to ca. 1600 Mt/yr in 2050 and ca. 2000 Mt/yr in 2100 (Figure 4a). While certain regions show a peak in steel consumption when approaching regional stock saturation, there is no equivalent consumptions peak on the global scale before 2100. This is because the very large populations of Developing Asia and Africa are assumed to accelerate their development late in the 21st century, thus keeping global demand on a high level. Around 2020, there is a local peak in global construction demand caused by the development in China.

Today, old scrap is mostly re- or down-cycled into construction steel, which is a large enough reservoir for steel of lower quality. This cannot be maintained throughout the whole century: Around 2025, old and new scrap together will exceed construction demand and old scrap alone will exceed it by around 2030, making it necessary to use end-of-life scrap in machinery or transportation. The technical challenge of using scrap in more demanding applications is discussed below. By 2050, old scrap supply will exceed final demand in China, Western Europe, and CIS (Figure 3).

The plateau in global final steel demand around 2030 in Figure 4a turned out to be an all-time high in primary production (Figure 5a). The subsequent rise of total steel demand was met by increasing secondary production. Between 2050 and 2060, EAF steel production can surpass BOF steel output, and the late 21st century can become the steel scrap age. A global peak in primary production around 2025 poses new challenges to the steel industry because there are large and young production assets for primary steel, especially in China, that have an economic life until 2060−2100. We applied the capacity model and considered two extreme cases of locating future primary steelmaking capacity in the different world regions:

In the case of ‘trade follows capacity’ (Figure 5b), uneconomic decommissioning could be avoided, but between 2040 and 2060, ca. 200 Mt/yr of blast furnace capacity would have to be taken out of operation before reaching end of technical life. Between 2020 and 2070, no new primary production assets were required.

The ‘capacity follows demand’-case (Figure 5c) lead to continued erection of new steel production capacity in India, the Middle East, Latin America, and Africa, but also resulted in

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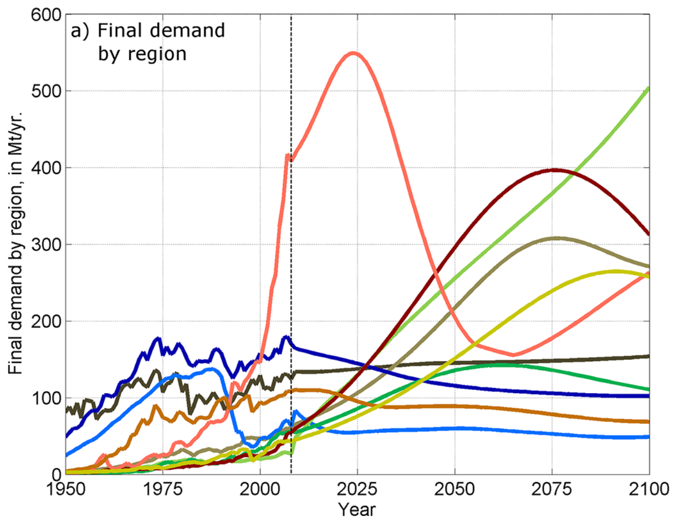

Figure 3. Final steel demand and old scrap supply by region.

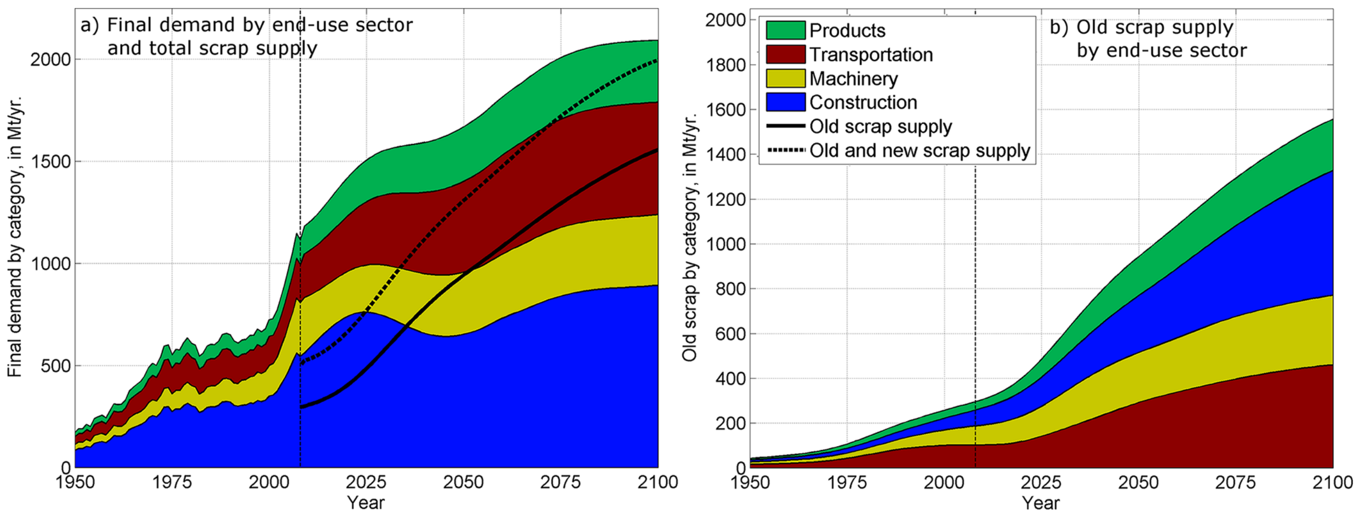

Figure 4. Total final steel demand and old scrap supply by end-use sector.

large amounts of uneconomic decommissioning (ca. 500 Mt/yr total capacity), in addition to ca. 100 Mt/yr of capacity being closed before reaching end of technical life, predominantly in China and Western Europe.

To test the robustness of the model parameter choices, we performed a sensitivity analysis of the central use phase parameters: population (±30%), saturation level (±2 tons), saturation time (±50 years for all developing regions except China, where a large and young steel industry allows for stable and fast stock growth[12]), and a ±30% change in product lifetimes. Only if steel stocks in all regions saturate by 2100, will there be a pronounced "peak steel" within the 21st century (Figure 6). For all other parameter changes the shape of both final demand and scrap supply remains mostly the same, which suggests that our qualitative forecasts on the future development are usefully robust under significant changes in the driving parameters. However, the actual production levels are subject to large uncertainties.

■ DISCUSSION

We address questions (1) and (2) from above as well as uncertainties and model limitations:

(1) Trends in Steel Demand and Scrap Supply. Our results show that steel demand in at least five out of ten regions is likely to peak within the 21st century, but that a global peak in total steel demand will occur only if stocks in all world regions have reached saturation by 2100. Global demand for primary steel may peak already around 2025, and there may be excess blast furnace capacity in the subsequent years.

Scrap flows will continue to rise significantly and even exceed final demand in some regions, and secondary steel production may surpass primary production in the second half of the century.

(2a) Challenges for Primary Steel Makers. Steelmaking facilities in Western Europe, Developed Asia, and China may become idle after demand peaks in these regions, but shipping finished steel to India, Latin America, and the Middle East, where demand grows, may prolong their operation time. The capacity model showed that merging the final demand from all regions into one global market, as in the "trade follows capacity"-scenario, allows all existing primary production assets to reach at least a 60 year lifetime, despite a falling demand for primary steel after 2025. A globalized steel supply could compensate for regional demand variations, and open markets for steel and scrap may facilitate the optimal use of existing

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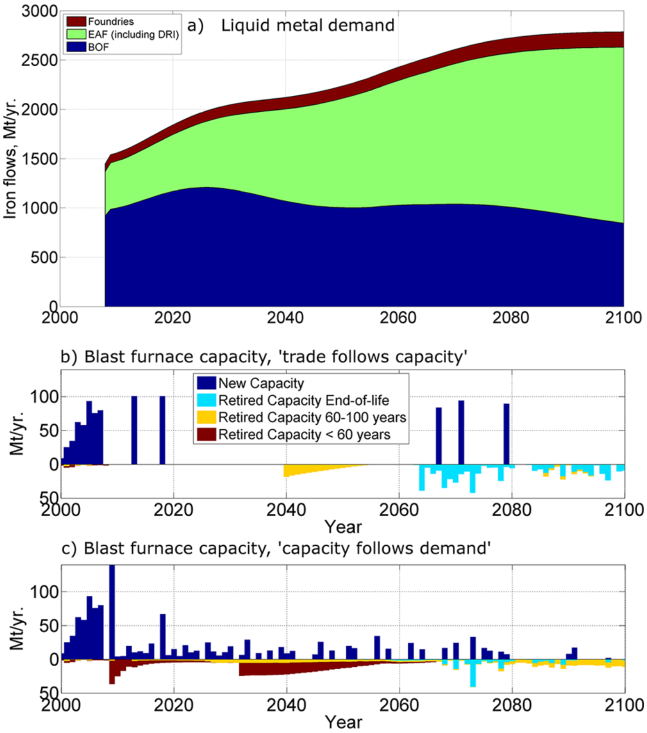

Figure 5. Supply of liquid metal and two extreme responses of primary steel suppliers.

assets. Alternatively, locating assets according to regional demand would give individual countries more control over this vital industry, but would likely lead to increasing overcapacity, declining prices, and subsequent recurrence of the 'steel crisis' elsewhere.

(2b) Challenges to Waste Management and Secondary Steel Makers. Given the population trends and our assumptions on future stock patterns, scrap supply in China, Western Europe, and CIS could exceed final steel demand after 2050. That, in theory, would allow these regions to operate closed steel cycles and shut down primary steel production, which requires that all manufactures switch to secondary steel. However, producing high-quality steels from secondary resources could be a challenge, because tramp elements, mainly copper and tin, can accumulate in the recycled material, which reduces ductility and may lead to surface defects during forming.[22,23] This concerns mainly the car industry and other manufacturers that depend on high quality or specialty steels. Improved sorting and material recovery in the waste management industries may reduce the contamination with tramp elements.[22] Sweetening, that is adding small amounts of primary steel to the melt in EAFs, is another way to keep the concentration of tramp elements low.[4] Another option is to export old scrap to developing regions with high demand in construction, where a copper concentration of up to 0.4% can be tolerated.[22]

The material quality within the different steel scrap classes may vary considerably.[24] Operators of secondary steel plants determine the mix of scrap from different classes for each EAF charge. They need to find a trade-off between material costs and the risk that the charge fails to meet the required specification.[24] Stochastic optimization routines such as a product recipe model help to identify scrap mixes that minimize material costs over a large number of EAF charges.[24,25] Combined with our scenarios on future scrap supply, these models could be used to determine the maximal amount of different steel grades that can be produced from the scrap accruing in a certain region.

Provided that effective measures to utilize all recoverable old scrap are implemented over time, the "steel scrap age" can commence in the late 21st century.

(2c) Challenges and Possible Environmental Consequences Related to the Location of Future Primary Steelmaking Capacity. Premature decommissioning of existing capacities may threaten the economic prosperity of steel companies and may lead to high local unemployment rates.[13] Industry and governments therefore have a natural interest in long capacity lifetimes and a strong motivation for continued investment to improve energy efficiency, which keeps the assets competitive and makes them adhere to environmental standards. The typical duration of a furnace campaign is 10−20 years,[26] which allows for periodic upgrades to latest technological standards. Contrarily, moving assets to a new location represents an option for more radical change by increasing the furnace volume or moving to a novel ironmaking technology. Future work needs to show which of the

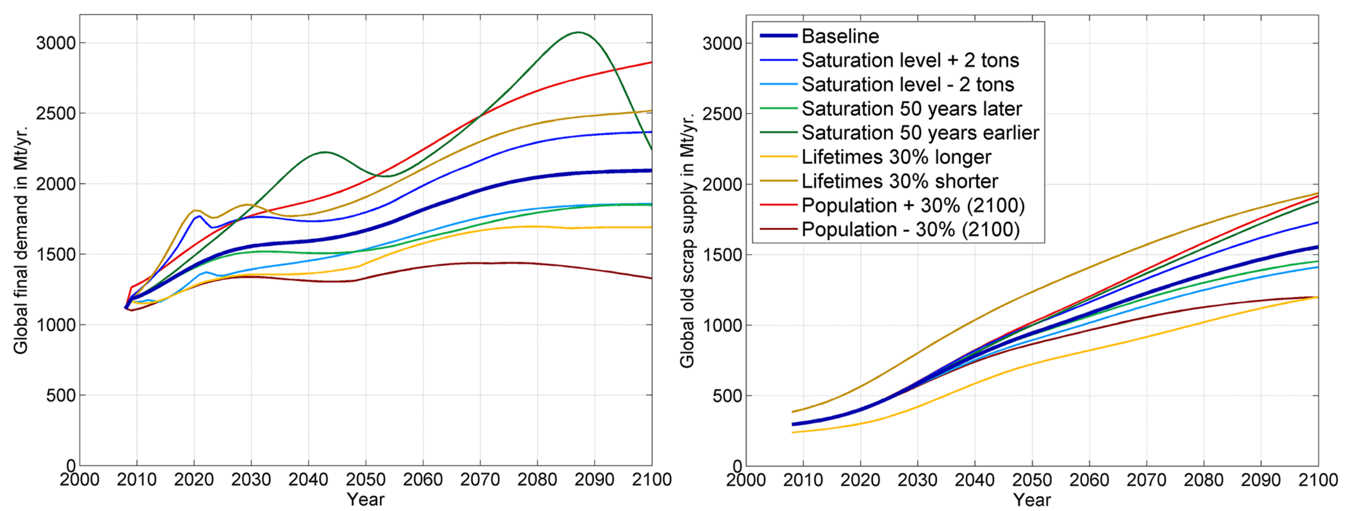

Figure 6. Sensitivity of final steel demand and supply of old scrap with respect to model drivers.

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two capacity scenarios discussed here is more likely to yield lower energy consumption and carbon emissions in the long run.

(3) Uncertainty and limitations. Forecasting steel demand over the entire 21st century involves large uncertainties as shown in the sensitivity analysis. It is not the actual numbers, but the patterns and trends that are reproduced under many different parameter assumptions, that make our forecasts robust: Previous work showed that under the assumption of saturating stocks, the occurrence of a demand peak in a certain region is insensitive to substantial changes in population, saturation level and product lifetime.[12] This work demonstrated that end-of-life scrap supply will continue to rise substantially and that secondary production will finally exceed primary production, irrespective of the parameter values chosen. We showed that global final demand will peak by 2100 if stocks all over the world saturate by then. These trends are central elements of the dynamics of the future steel cycle; they need to be considered when making reliable projections on steel demand and recycling potential in different regions.

Our results were obtained by extrapolating historic steel use patterns in the developed world to the entire globe. The central assumption of future stock saturation is the main limitation of our approach. Although it is based on solid historic evidence, there is no mechanism that leads to a certain stock trajectory. Stocks in buildings and infrastructure tend to accumulate,[10] and possible regional overcapacities could lead to falling prices that in turn stimulate steel consumption, which may lead to larger stocks. On the contrary, increasing awareness of climate change, energy supply constraints, and other environmental impacts may make us rethink the way we produce and use materials. The saturated per capita stocks in several countries demonstrate that a certain amount of steel is *sufficient* to achieve high human development;[27] and the follow-up publication will examine how service can be decoupled from material stocks in order to further save primary steel and energy and to substantially reduce the carbon footprint of the steel cycle.[14]

■ ASSOCIATED CONTENT

Supporting Information

We provide the complete system definition, the model equations, documentation of data sources and treatment, model calibration, and additional results. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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