# The Steel Scrap Age

by

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# The steel scrap age

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## ABSTRACT

Producing steel accounts for 25% of industrial carbon emissions. Long-term forecasts of steel demand and scrap supply are crucial for developing roadmaps of how the steel industry could respond to industrialization and urbanization in the developing world while simultaneously reducing its carbon footprint. We present a dynamic stock model that estimates future demand for final steel and the supply of scrap for ten world regions, assuming that per capita in-use stocks will saturate eventually, as evidence from developed countries suggests. We explore the response of the entire steel cycle, in particular the split between primary and secondary steel production.

We find that 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 develop a capacity model to demonstrate how extensive trade of finished steel could prolong the lifetime of existing Chinese production assets. Secondary production will more than double by 2050, and it may surpass primary production between 2050 and 2060, thus ushering in the global steel scrap age.

## Introduction

Steel production is one of the largest industrial sectors and it accounts for ca. 25 % of industrial and 9% of all anthropogenic energy- and process-related greenhouse gas emissions.[1] Further expansion of the steel industry is not limited by resource availability: Iron ore and coal are abundant and distributed 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. In order to develop roadmaps for substantial emission reduction within the steel sector, stakeholders in the steel industry and policy makers need information on future trends in steel use, demand, and recycling potentials in different world regions. This knowledge is crucial for decisions on the allocation of new production facilities, the choice between primary and secondary production route, and ultimately to lower the sectoral carbon footprint.

Long-term forecasts on global steel demand for the year 2030 and beyond have been published by both international institutions[4-6] and several scholars.[7,8] All approaches, except Hatayama et al.,[8] extrapolate recent growths rates in steel consumption,[7] or rely on exogenous

GDP projections and a function defining how steel consumption is coupled to GDP, as in the World Energy Model[4] and the steel module of the POLES model.[6]

Steel-bearing products provide service for several decades[9] and hence, the *in-use stock* of steel rather than the *consumption flow* is a more adequate measure of the different services provided by steel, and steel consumption is only a means to build up or maintain the in-use stock, which provides the actual service to society. The commonly used extrapolations of steel consumption do not consider the development of the in-use stock and can therefore neither connect consumption to the actual service provided, nor estimate future supply of post consumer scrap from products leaving the in-use stock at the end of their lifetime.[10] Instead, availability of post-consumer scrap is often taken for granted.

Models that derive demand from assumptions on future stocks and product lifetime have been used to forecast steel demand and scrap supply on the country scale[11] and have recently been extended to the global scale:

Hatayama et al.[8] use a multi-regional stock-based model to estimate future global steel demand until 2050 and track three end-use categories: buildings, civil engineering (infrastructure), and passenger vehicles. While their work covers about 80% of the steel stock in developing countries, it includes only the use phase of steel and does not investigate how the steel industry and waste management could respond to future steel demand and scrap supply. Since most emissions associated with steel occur in the production phase and vary greatly between primary and secondary production,[5] modeling the entire steel cycle is a crucial step toward envisioning the future structure of the steel industry and creating mass-balance consistent long-term scenarios on climate change mitigation within the sector.

In the OECD countries, per capita stocks of steel in use lie between 6 and 16 tonnes.[9,10] Per capita stocks in several developed countries have leveled out in the range of 14 +/- 2 tonnes, and another group of ca. ten countries with stocks between 10-14 tonnes shows signs of leveling out in the same range.[9] 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.[10] In previous work[11] we built scenarios for the Chinese steel cycle assuming per capita stock will saturate in the future, and we find a peak in steel demand that is insensitive to significant changes of both saturation level and lifetime: As steel stocks in China reach the level of other industrialized countries, they may saturate as well, demand may plummet, and a new *steel crisis* may be inevitable.

This work extends our work on China to global coverage and examines the consequence of a worldwide future saturation of per capita in-use stocks of steel on production capacities and material flows in the global steel cycle. In particular we address the following questions:

(1) What trends in regional steel demand and scrap supply follow from a saturation of per capita stock everywhere in the world? Will steel demand peak in different regions as it has been observed in several industrialized countries?
(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?
(3) How robust are our findings and what are main limitations of our approach?

The model allows for an inclusion of energy demand and greenhouse gas emissions as well as to examine the potential impact of energy and material efficiency, and this is developed in a connected paper by Milford et al.[12]

## Methodology

To answer the questions above we need a model of the entire steel cycle, which covers mining, primary and secondary steel production, fabrication, use, and waste management (Figure 1). The different processes are connected by iron flows and the mass balance for iron holds for each process. The complete system definition and the model approach, as well as all data sources and our analysis of the data are covered in the supplementary information (SI).

The time series of steel stocks in industrialized countries[9,10] show that decoupling of steel use and economic development may occur once steel stocks reach a certain level. We base our scenarios on the hypothesis that *eventually, all regions will enjoy a similar service from steel stocks as the industrialized countries do today.* For this article we assume that service level is coupled to stock level and that all regions follow the stock pattern observed in the developed countries with the most mature steel stocks. In the connected paper we explore how service level and material use can be decoupled.[12]

The in-use stock is the model core; its size serves as a measure of the service that steel provides to society. There are two ways of connecting final demand, stocks, and discards with each other: For the years until 2008, we know the apparent final consumption of steel from previous work.[9] A lifetime model with typical residence times determines the fraction of final consumption that already has been discarded,[13] and the rest has accumulated as stock in use. For the future years we want to determine the inflow from a given per capita stock trajectory and hence we need an inverse approach: In a year-by-year calculation we first determine the annual discards from past consumption using the lifetime model, and then we determine final steel demand from mass balance (Equation 1):

$$\text{Final demand} = \text{Inflow} = \text{Outflow} + \text{Stock Change} \tag{1}$$

Upstream and downstream processes are 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 is determined by a linear model, which contains all transfer coefficients quantified by Cullen et al.[14] and which is driven by final steel demand and total discards. The split between primary and secondary steelmaking is chosen so that all available scrap is recycled, thus ensuring the system-wide mass balance.

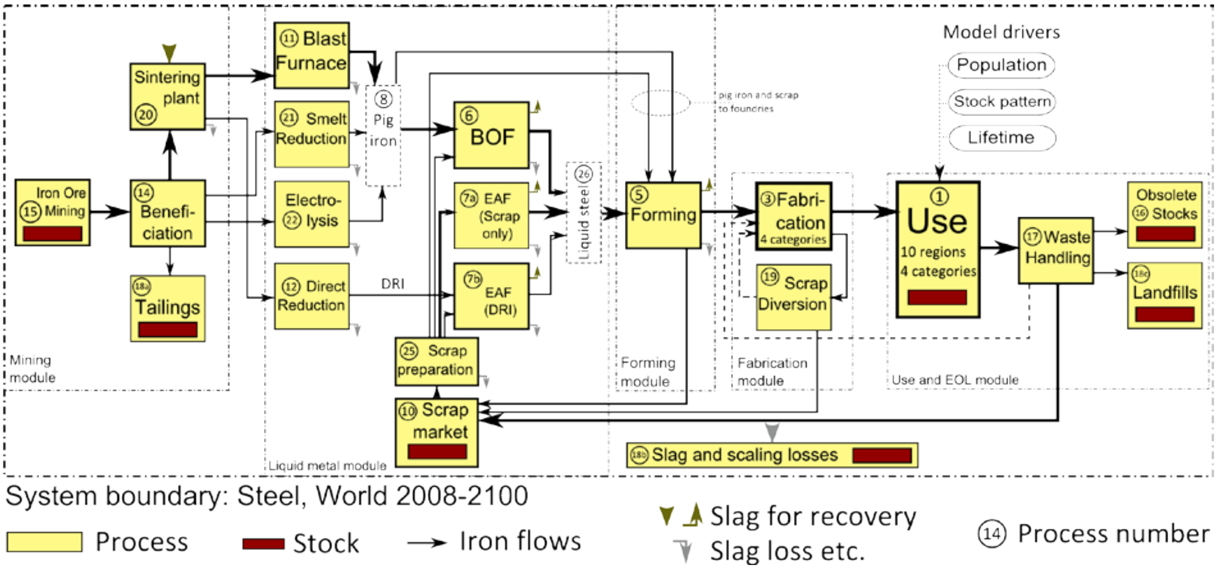


**Figure 1:** System definition. BOF = basic oxygen furnace, EAF = electric arc furnace, DRI = direct reduced iron.

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

**Geographic scale:** Country-specific forecasts require an accurate assessment of existing stocks and country-specific assumptions on future development. This approach is limited by the available data on steel end use and product lifetime. On the other hand a global model could not reflect the differences between industrialized countries and the developing world. Therefore, we consider ten regions comprised 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 is modeled on the regional level; for upstream and downstream processes we aggregate flows to the global scale due to the large amounts of steel traded and because there is a global market for steelmaking technology.

**Time horizon:** Most of the steel produced goes into buildings and infrastructure, which have an observed lifetime of many decades, sometimes even centuries.[15] The long economic lifetime of assets in steel production also requires long-term modeling of at least 60 years (SI pp. 23-25). In contrast, climate change mitigation requires significant action within the next few decades. We use a time horizon of 2100 for modeling the production, use, and recycling in the steel cycle, and 2050 as target year for the scenarios on energy consumption, material efficiency, and emissions explored in the connected paper.[12]

**End-use sectors:** Quality requirements and lifetime vary greatly between buildings, cars, water turbines, laptops, and other steel-bearing products. There are no standard end-use categories reported in steel statistics; we use 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 95% of the saturation level is coupled to other factors, especially economic development.[10] We could try to infer the saturation time from exogenous GDP estimates, but this would merely shift the uncertainty from our own estimate to an exogenous forecast 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 has been used to model future per capita stock.[8,11] After fitting the curve to the latest stock value and its growth rate, only one additional parameter, which can be either the saturation level $\hat{S}$ or the saturation time $t_S$, can be chosen. In order to make independent choices for saturation level and time for the different regions we need to add one parameter. We propose a generalized logistic curve, which contains a double exponential function and is a synthesis of the logistic curve and the Gompertz model, which is commonly used to model saturation phenomena (Equation 2):[16]

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

where t is the time, $\hat{S}$ the saturation level, and $S_0$ the 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 stock curve is tangential to the latest historic stock in $t_0$=2008 and ii) the stock reaches 95% of the saturation level at a given time $t_S$.

**Parameter choice:** The baseline scenario comprises population estimates used in the IPCC AR3;[17] our best estimates of stock saturation levels and lifetimes[9] (Table 1); a gradual improvement of end-of-life scrap recovery rates, estimated by WorldSteel;[3] and the assumption that for each year, all available scrap is fed back into steelmaking. According to historic evidence[9] we assume the following saturation levels for the per capita stock: 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 need to be adapted slightly to better fit the individual historic development (Figure 2a). Steel stocks in China have been estimated to saturate around 2050[11] and we assume that Latin America and the Middle East will follow 50 years later, while saturation on the global scale is assumed to happen around 2150.

**Table 1:** Saturation level by category and region; saturation time.

| Saturation Level (tonnes) and lifetime (years) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Region | Transportation | | Machinery | | Construction | | Products | | Total Stock | Saturation time $t_S$ |
| **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 | 0.9 | 20 | 12 | 50 | 0.8 | 10 | **14.7** | **2020** |
| **10** | **Developing Asia** | 1.5 | 20 | 1.6 | 30 | 10 | 75 | 0.6 | 15 | **13.7** | **2150** |

The curves in Figure 2a reflect a development to a service level comparable to the present level in developed countries. According to the regional stock patterns assumed, global per capita stock will grow from the present level of 3.7 tons to ca. 6.5 tons in 2050 and ca. 10 tons in 2100 (Figure 2b). Construction makes up 75 % of stocks, followed by transportation (ca. 10%) and machinery (ca. 8%). In around 2060, the global average per capita stock level will be about half the saturation level of industrialized countries.

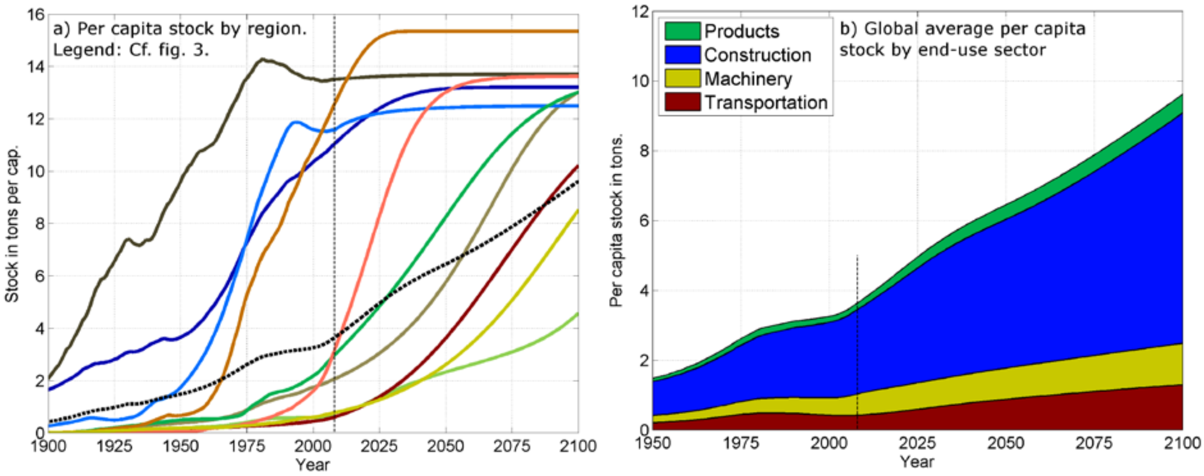


**Figure 2:** Assumptions on future stock patterns and resulting average global stock by end use sector.

**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. Blast furnaces, integrated steel plants, and the supporting infrastructure have very long economic lifetimes of 60-100 years (SI pp. 23-25). In periods of low steel demand, idle blast furnaces can hibernate for several years without being torn down (SI pp. 23-25). In times of increasing demand the average overcapacity margin is typically 8%,[18] and when demand stalls, overcapacities are demolished after a waiting period that we assume to be five years, beginning with the oldest assets. We consider demolishing after less than 60 years of operation as uneconomic, and facilities reaching 100 years lifetime are taken out of use for technical reasons and replaced by new capacity if there is a demand. The age structure of the primary steel sector in 2008 is determined using historic regional pig iron production figures.[9]

For the future development we consider two cases: i) In the globalized case – ‘trade follows capacity’ – we assume 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 assume that different world regions build up their own capacity as they develop, e.g., due to concerns about resource security and independency, irrespective of whether there is steel production capacity available elsewhere. A full description of the allocation of future production capacities is given on pages 23-26 in the supplementary information.

## Results

Figure 3 relates to question (1) on regional demand and scrap supply, Figures 4 and 5 deal with question (2) on what challenges the industry is likely to face, and Figure 6 addresses question (3) on the uncertainty of our results.

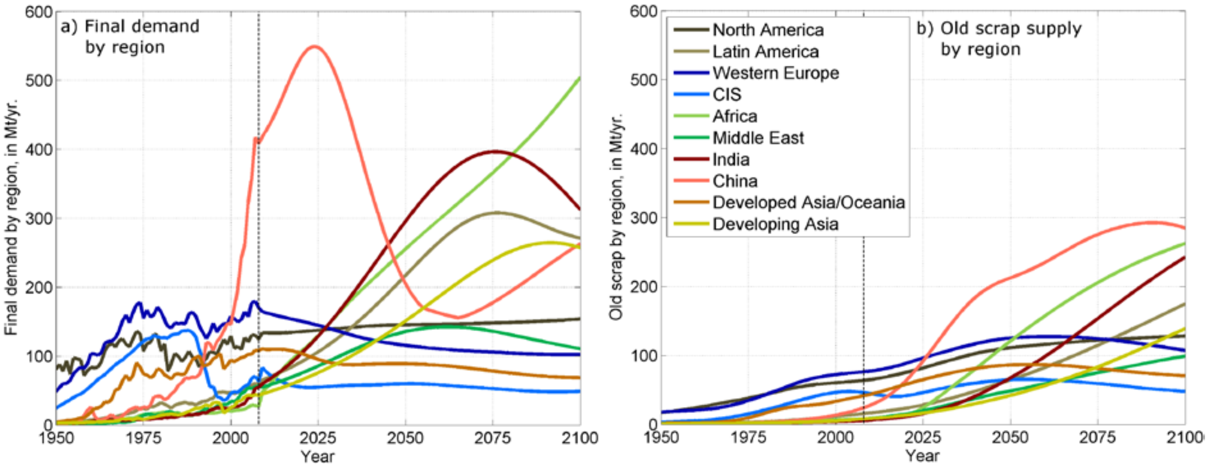


**Figure 3:** Final steel demand and old scrap supply by region.

The faster the stock reaches saturation the more drastically final demand drops after peaking in the years of fastest stock growth (Figure 3a): China shows a huge peak with 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 slight increase in demand for North America; in combination with a shrinking population, it leads to an almost 50% decrease in demand for Europe by 2100.

Regional scrap flows change less rapidly (Figure 3b): While today, most scrap is sourced in the developed world, this will change from around 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).

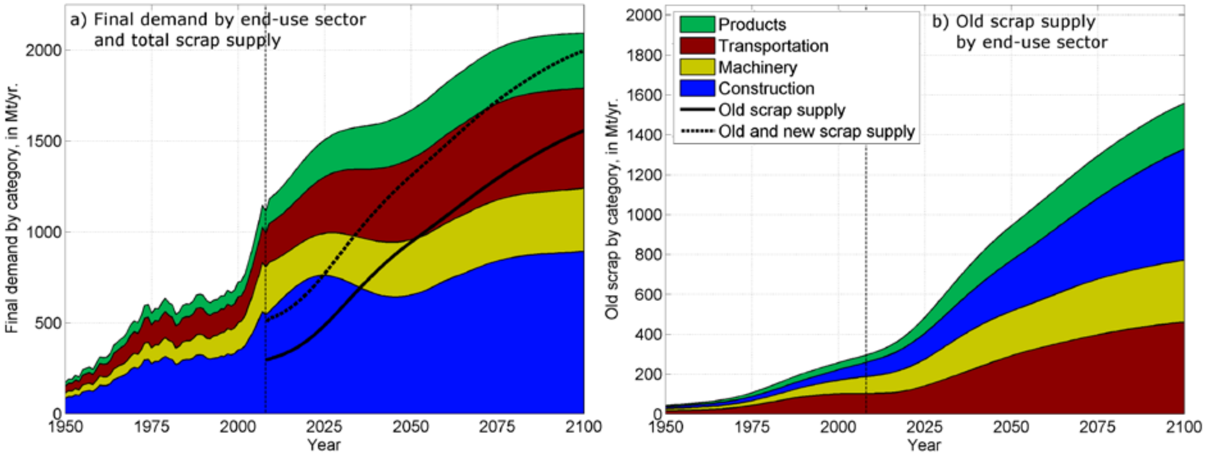
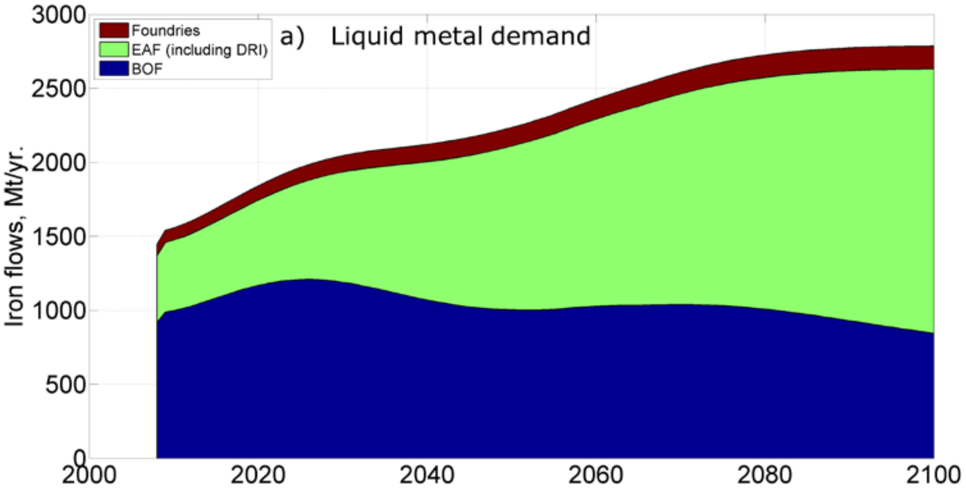


**Figure 4:** Total final steel demand and old scrap supply by end-use sector.

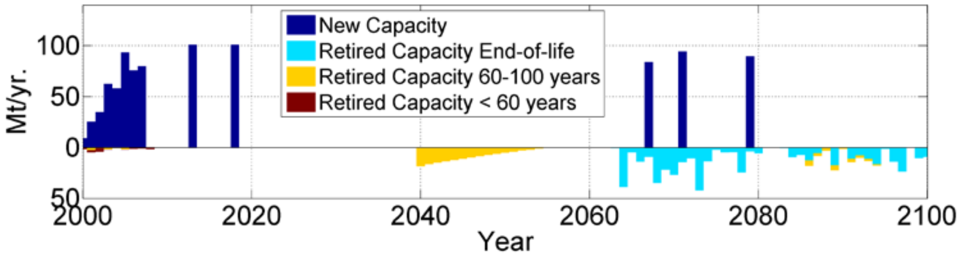
Aggregated final demand will increase from 1100 Mt/yr in 2008 to ca. 1600 Mt/yr in 2050 and ca. 2000 Mt/yr in 2100 (Figure 4a). While certain regions show a peak in steel consumption when approaching regional stock saturation, there is no equivalent consumptions peak on the global scale before 2100. 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 pattern cannot be maintained throughout the whole century however: 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).

We show the split between primary and secondary production as well as two ways in which primary producers could respond to future demand (Figure 5).



b) Blast furnace capacity, 'trade follows capacity'



c) Blast furnace capacity, 'capacity follows demand'

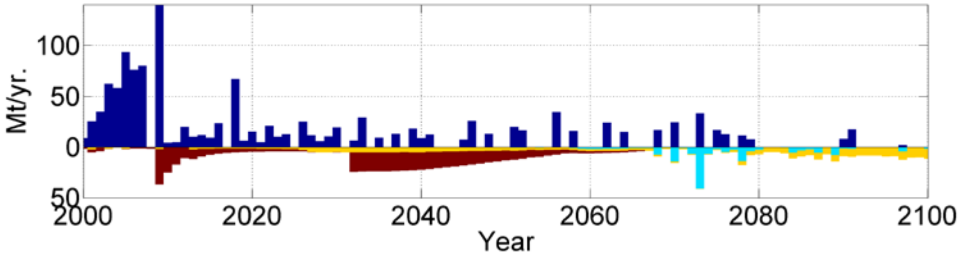


**Figure 5:** Supply of liquid metal and two extreme responses of primary steel suppliers.

The plateau in global final steel demand around 2030 in Figure 4a turns out to be an all-time high in primary production (Figure 5a). The subsequent rise of steel output comes from increasing secondary production and between 2050 and 2060, EAF steel production will surpass BOF steel output, and the 21st century will 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 production, especially in China, that have an economic life until 2050-2070. We apply the capacity model and consider two cases of how future primary steelmaking capacity can be located in the different world regions:

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

The ‘capacity follows demand’-case (Figure 5c) leads to continued erection of new steel production capacity in India, the Middle East, Latin America, and Africa, but also results in large amounts of uneconomic decommissioning (ca. 500 Mt/yr total capacity), in addition to ca. 100 Mt/yr of capacity being closed before reaching the end of its technical life, predominantly in China and Western Europe.

To test the robustness of the model parameter choices we perform 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), 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.

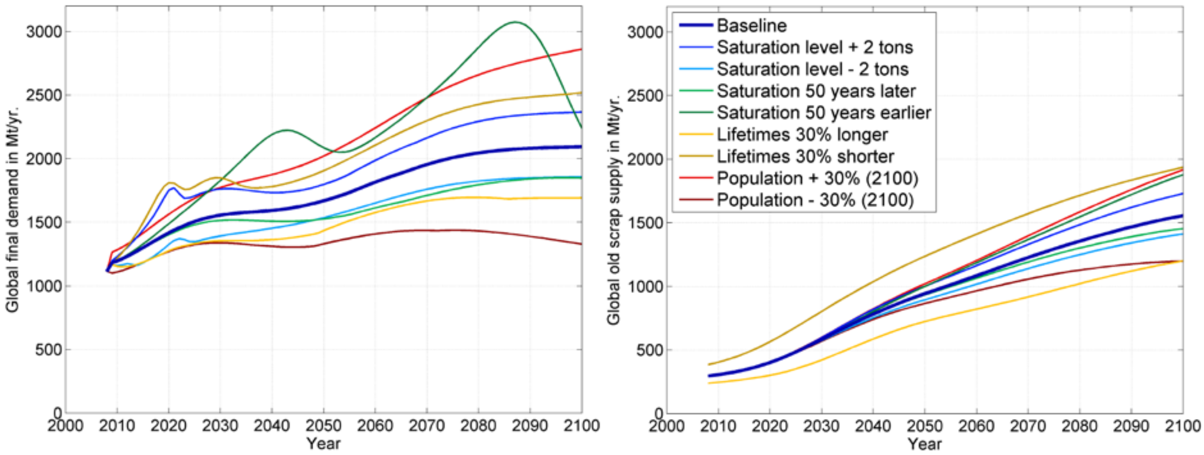


**Figure 6:** Sensitivity of final steel demand and supply of old scrap with respect to model drivers.

## Discussion

We address the three questions posed above:

**(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 all global stocks have reached saturation by 2100. However, global demand for primary steel will reach a peak much earlier than this, around 2025, after which we will have excess blast furnace capacity but require additional electric arc furnaces.

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

**(2) 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 shows that merging the final demand from all regions into one global market allows all existing assets in primary production 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 assets. Alternatively, distributing assets according to regional demand would give the different countries more control over this vital industry, but would likely increase overcapacity, declining prices, and subsequent recurrence of the *steel crisis* elsewhere.

**(2) Challenges to waste management and secondary steel makers:** By 2050 the steel industry is likely to process three times more scrap than today, while final demand may only increase by 25% compared to 2008. This not only has consequences for production capacities and the carbon footprint, it may also make it more difficult to produce high-quality steels, because end-of-life scrap is a more diverse and contaminated resource than forming or fabrication scrap. According to the population trend and our assumptions on future stock patterns, scrap supply in China, Western Europe, and CIS could exceed final demand after 2050, which, in theory, would allow these regions to operate closed steel cycles and shut down primary steel production. This would require however, that all manufactures to switch to secondary steel, which may be especially challenging for the car industry and other manufacturers that depend on high quality or specialty steels. An alternative is to further develop the global scrap market where excess scrap is traded to developing regions with high demand in construction where it can be used to produce rebar and girders that tolerate a higher level of contaminations than quality steel. Eventually however, scrap will have to penetrate other sectors than construction. Sweetening, that is adding small amounts of primary steel to the melt in EAFs, may help to maintain the quality of secondary metal. This process is already common in recycling of aluminium beverage cans.[19]

The 21st century can become the steel scrap age, provided that steel producers change their capacity mix and that the actors in the waste management industry improve sorting and material recovery to maintain sufficiently high material quality while maintaining or increasing the end-of-life recovery rate. The importance of large integrated steel plants will decline as more scrap-fed mini-mills emerge. Integrated steel plants could be equipped with EAFs as liquid metal feeders to utilize existing casting and rolling capacities in regions where demand for primary steel is dropping. This may lead to higher transportation costs, however, as secondary production facilities are typically located close to large metropolitan areas, which are the main sources of post-consumer scrap.[20]

**(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 sets, that make these 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.[11] This work demonstrates that end-of-life scrap supply will continue to rise substantially and secondary production will finally exceed primary production, irrespective of the parameter values chosen. We have shown 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 attempting to make reliable projections on steel demand and recycling potential in different regions.

Our results are based on the scaling-up of historic steel use patterns in the developed world to the entire globe. The central assumption of future stock saturation is also 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,[9] and possible regional overcapacities could lead to falling prices that in turn stimulate steel consumption, which may lead to larger stocks. On the other hand increasing awareness of climate change, energy supply constraints, and other environmental impacts may make us re-think 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;[21] 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 further reduce the carbon footprint of the steel cycle.[12]

## ACKNOWLEDGEMENT

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## SUPPORTING INFORMATION AVAILABLE

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

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