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Outlook of the World Steel Cycle Based on the Stock and Flow Dynamics

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We present a comprehensive analysis of steel use in the future compiled using dynamic material flow analysis (MFA). A dynamic MFA for 42 countries depicted the global in-use stock and flow up to the end of 2005. On the basis of the transition of steel stock for 2005, the growth of future steel stock was then estimated considering the economic growth for every country. Future steel demand was estimated using dynamic analysis under the new concept of "stocks drive flows". The significant results follow. World steel stock reached 12.7 billion t in 2005, and has doubled in the last 25 years. The world stock in 2005 mainly consisted of construction (60%) and vehicles (10%). Stock in these end uses will reach 55 billion t in 2050, driven by a 10-fold increase in Asia. Steel demand will reach 1.8 billion t in 2025, then slightly decrease, and rise again by replacement of buildings. The forecast of demand clearly represents the industrial shift; at first the increase is dominated by construction, and then, after 2025, demand for construction decreases and demand for vehicles increases instead. This study thus provides the dynamic mechanism of steel stock and flow toward the future, which contributes to the design of sustainable steel use.

Introduction

Recently, the use of various substances such as mineral resources, fossil fuels, foods, water, and air has been discussed under the concept "sustainable use". For metals in particular, the way to sustainable use for the future must be explored promptly because mineral resources are nonrenewable. As the mineral resources in the lithosphere turned out to be limited, the construction of a "sound material cycle" in the anthroposphere becomes an important theme. In the anthropogenic metal cycle, products used in human society are regarded to have a recycling potential in the future. These urban resources are called "in-use stock", or simply "stock". The exploration of material stock and surrounding flows such as material consumption for products or waste stream after use has been recognized as a significant issue. This situation has triggered the development of the MFA/SFA (material flow analysis/substance flow analysis), and some MFA/SFA studies estimate the distribution of various materials across the world, for example, steel (*1*), copper (*2*), zinc (*3*), silver (*4*), chromium (*5*), and nickel (*6*). These studies present 1-year snapshots of material behavior across the world and offer some precious insights related to the material cycle. Still, to exploit the results of MFA for long-term perspectives or future-oriented studies, the MFA should illustrate the transition of stocks and flows with time based on a comprehension of dynamic mechanisms in society. The material flows are dependent on various factors, such as economic parameters (GDP, metal price, energy price, etc.) and technological restrictions (ore grade, energy intensity, etc.) (*7*). The dynamics have often been discussed from the economics viewpoint that explores the relationship between metal price and demand (*8, 9*), and more recently, several studies called "dynamic MFA" were published, which relate the stocks and flows considering the product lifetime in the material cycle (*10*–*13*). These studies show the historical changes in material stock and discard at country level. In a discussion of the efficient use of urban resources, however, the supply demand balance of discarded scrap should be considered globally because materials are actively traded across countries in various forms, i.e., ore, material, product, and scrap (*14*).

Some dynamic MFA studies sometimes present the forecast of material cycles. When the dynamics are well described, appropriate scenarios provide the transition of the entire material cycle in the future. Most of these studies forecast the future demands of materials, for example, using the intensity of use hypothesis (*7, 15, 16*). In these studies, demand flow is regarded to be the driver of the material cycle. Nevertheless, the dynamic mechanism of the material cycle is so complicated and unexplained that other approaches to discuss the future material cycle should be attempted. One of the alternative approaches is to focus on the material stock. The demand arises when people feel a deficiency in supply in the society; therefore, it is a considerable attempt to regard stock as the driver of the material cycle. A few studies estimate the future material stock (*17*–*19*); however, the dynamic effect on the material cycle is not well explained. Demand and discard flows in the future can be derived from the forecast of the stock within the stock and flow dynamics (*14*). The new perspective to the discussion about anthropogenic material cycle in the future would be provided when stock as a driver and surrounding flows are analyzed globally.

This paper, which focuses on steel, the most widely used metal, provides the global resource potential in the anthroposphere and prospects of steel demand using dynamic MFA. The 42 country-level MFAs are integrated as a global analysis, and these countries accounted for 85% of the world steel consumption in 2005. In the former part of this paper, the dynamic MFA estimates the historical change in in-use stock and discard of steel by 2005. In the latter part, the future steel demand by 2050 was estimated from the stock increase under the assumption that the steel stock saturates as a country develops.

Methodology

Static Analysis and Dynamic Analysis. The MFA/SFA analyzes the material's behavior; for example, it estimates the amount of in-use stock and discarded materials contained in end-of-life products. There are two types of approaches to analyze material flow, namely static and dynamic analyses.

In static analysis, material stock and flow in a certain year is analyzed using the relevant data for that year. Gerst (*19*) calculated the in-use stock of copper from the following equation.

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$$S_{i,t} = \Omega_{i,t}\psi_{i,t} \tag{1}$$

The subscript i indicates technology where copper is used, and t indicates time. $\Omega_{i,t}$ is a function that calculates the in-use stock of a copper-containing technology (e.g., length of power distribution cable), and $\Psi_{i,t}$ is a function that calculates the copper content of the technology (e.g., kilograms of copper per length of power distribution cable). Equation 1 indicates that the in-use stock in time t is calculated only from parameters for that year. The static analysis is often expressed as a bottom-up approach because the total material stock is calculated by counting material used in the existing products. This approach is effective when $\Omega_{i,t}$ and $\Psi_{i,t}$ are recorded precisely. For example, vehicle ownership is registered; therefore, material stock in vehicles would be calculated with a high accuracy when the material content in vehicles is well surveyed. For most products, however, it is difficult to find data on the values $\Omega_{i,t}$ and $\Psi_{i,t}$. This is a large obstacle for a bottom-up approach to illustrate the entire material flow in the society.

In the dynamic analysis, material stock and flow in a certain year is derived from the input, stock, and earlier output. A material balance for year t is described as in eq 2

$$S_t = S_{t-1} + I_t - O_t \tag{2}$$

where I indicates an input to the society and O indicates an output from society. Considering the product's lifetime T, the relationship between input and output is described as follows (*20*):

$$O_t = I_{t-T} \tag{3}$$

Substitution of eqs 2 and 3 gives eq 4.

$$S_t = S_{t-1} + I_t - I_{t-T} \tag{4}$$

Considering that the oldest product existing in year t is input into year $t - T + 1$, repeated substitution of eq 4 leads then to

$$S_t = \sum_{\tau=t-T+1}^{t} I_\tau \tag{5}$$

Equation 5 implies that the stock is calculated from the time series input. The dynamic analysis for stock accounting is therefore expressed as a top-down approach. Some studies assumed that the product lifetime follows a probability function. Assuming the probability function of discards against product age a as $g(a)$, eq 3 is converted into eq 6:

$$O_t = \sum_{a=1}^{a_{\max}} I_{t-a}g(a) \tag{6}$$

Therefore, eq 5 is converted into eq 7.

$$S_t = \sum_{a=1}^{a_{\max}} I_{t-a}\left(1 - \sum_{\tau=1}^{a} g(\tau)\right) \tag{7}$$

The dynamic analysis is useful for understanding the transition of material flow with time, and the dynamic analysis clearly shows what spread effect would appear when a part of the system changes. This advantage contributes well to design and management of future material use; therefore, in this study we analyzed the world steel use with dynamic MFA.

Data Preparation for Dynamic MFA. The lifetime of steel differs according to the products steel is used for. Therefore, in the dynamic MFA, the amount of steel input to society (described as "input" in this paper) and the lifetime of steel must be prepared specifically for every end use. For most countries, however, only the total apparent consumption is available (*21*); therefore, the share of each respective end use must be inferred. In this study, the share was obtained from the report (*22*) published at random times by the Japan Iron and Steel Federation. The documents report the share of eight end uses, namely construction, electrical appliances, machinery, vehicles, shipbuilding, containers and packaging, semiproducts, and other products country by country. We arranged these data, divided the share of construction into civil engineering and building (see Supporting Information), redistributed the shipment for semiproducts to the rest, and supplemented lacking data with linear interpolation (the share before 1980, the oldest report, was assumed to be the same as in 1980). Aside from this, statistics of steel consumption for each end use were available for the United States (*23*) and Japan (*24*), and therefore we used them instead.

Then, yield losses in the fabrication and manufacturing processes were counted. Fabrication and manufacturing processes yield prompt scrap, which is sold to the market. Therefore, the yield ratio was determined for each end use. Furthermore, the steel trade induced by the trade in finished products was considered for vehicles. It is called indirect or hidden trade. While trade of steel products such as plates and bars are recorded, indirectly traded steel must be estimated by the bottom-up approach (see eq 1).

Lifetimes were respectively determined for three groups of geographical areas: Europe, Commonwealth of Independent States (CIS), and Africa; North and South America; and Asia, Middle East, and Oceania. Lifetime data were taken from previous MFA/SFA studies focusing on relevant countries. For example, lifetimes in the United States were applied to North and South America.

Further information on yield losses, indirect trade, and lifetime of the products are given in the Supporting Information.

Forecast of the Future Steel Use. The prospects of steel demand have a notable contribution on the design and management of steel use toward the future. Compared with the soaring steel consumption during the 20th century, the United States, Japan, and some other countries show far less steep growth of steel consumption in recent years. Generally, material demand for new houses, roads, vehicles, and various necessities becomes stable as a country develops, and consumer preferences shift toward services, computers, and other less material-intensive goods (*25*). The intensity of its steel consumption is also reduced by technological advancement in processes and substitution with other materials such as aluminum and plastic. The concept that the growth of material consumption or stock would slow down is widely used in forecasting material use.

In forecasting the material consumption, several researchers consider the indicator called "intensity of use". Intensity of use is calculated as material consumption per GDP, as described in eq 8.

$$\begin{aligned}\text{intensity of use} &= \frac{\text{material consumption}}{\text{GDP}} \\ &= \frac{\text{material consumption}}{\text{total value of production}} \times \frac{\text{total value of production}}{\text{GDP}}\end{aligned} \tag{8}$$

Future steel consumption was estimated based on the intensity of use hypothesis (IU hypothesis): the intensity of use rises first and then falls as per capita income grows, and the resulting curve shows an inverted U-shape. Some studies supported the hypothesis by showing historical trends of intensity of use, which indicates an inverted U-shaped relationship (*7, 25*). The hypothesis has been leveraged for estimating the intensity of use in the future, and then future material consumption was estimated under a certain GDP growth scenario (*7, 15, 16*).

Another approach is to forecast the material in-use stock. Equation 7 seems to indicate that the stock is driven by the input flows; however, it is also presumable that the stock is driving the input flows (*18*). Some researchers attempted to forecast the change in stock, which can lead to future demand and discard estimation. In the forecast, it seems to be a rational consideration that material stock would not increase infinitely. Actually, Müller et al. (*13*) indicate that per capita steel stock in the United States remains at a constant level (12 t/capita) from the early 1980s. Some studies estimated future material stock by assuming that its increase follows an S-shaped curve. Toi and Sato (*17*) forecasted the steel stock in Japan by 2050 using the logistic function (eq 9)

$$S_t = \frac{S_{\mathrm{sat}}}{1 + \exp(\alpha - \beta \times t)} \tag{9}$$

where S_t is the total stock in year t, S_{sat} is a saturation value of total stock, and α and β are parameters. In an earlier report (*14*), we have forecasted the aluminum stock in Europe, the United States, Japan, and China using a similar logistic function (eq 10).

$$s_t = \frac{s_{\mathrm{sat}}}{1 + \exp(\alpha - \beta \times \mathrm{GDP}_t)} \tag{10}$$

Compared with eq 9, the variable t is replaced with per capita GDP, and stock is handled in per capita values as well (therefore, here S_{sat}, which denotes total stock, was replaced with s_{sat}, which denotes per capita stock). In ref *14*, the future aluminum input is also estimated by combining the dynamic MFA and the forecast of stock (note that the net addition to stock is not equal to the input; see eq 2). The input in year t is described from eqs 2 and 6 as

$$I_t = S_t - S_{t-1} + \sum_{a=1}^{a_{\max}} I_{t-a} g(a) \tag{11}$$

The first and second terms on the right side of eq 11 are calculated as the product of population and s_t for each year, which estimates the net addition to stock. If I_t is known for $t = t_0$, then I_{t0+1} can be calculated because the third term is derived from I_t before $t = t_0$. Therefore, the input in the future was calculated sequentially from the latest data.

Using the latter approach, in this work we estimated the future steel stock by 2050 for three major end uses: civil engineering, building, and vehicles. The in-use stock for civil engineering and building end uses was estimated using eq 10. The in-use stock for vehicles was calculated from the data of vehicle ownership and steel weight per vehicle. The growth of vehicle ownership in each country was estimated as an S-shaped curve, using the Gompertz function employed by Dargay et al. (*26*), as shown in eq 12.

$$s_t = s_{\mathrm{sat}} \exp(\alpha \exp(\beta \times \mathrm{GDP}_t)) \tag{12}$$

The three parameters s_{sat}, α, and β in eqs 9 and 12 must be determined in executing the forecast. For example, these values can be determined with nonlinear regression on plot data of the historical relationship between GDP and s_t (*1*). The regression analysis provides reliable parameters when the plot data becomes S-shaped to some extent. Conversely, when the plot data shows only the beginning of an S-shape (as in the case of many developing countries), these values might not be estimated adequately. In particular, s_{sat} should be determined carefully because these values highly contribute to the total amount of stock. We therefore characterized the s_{sat} values for respective countries using social parameters, such as population density and urbanization (urbanization is an index that represents the population intensity in an urban area).

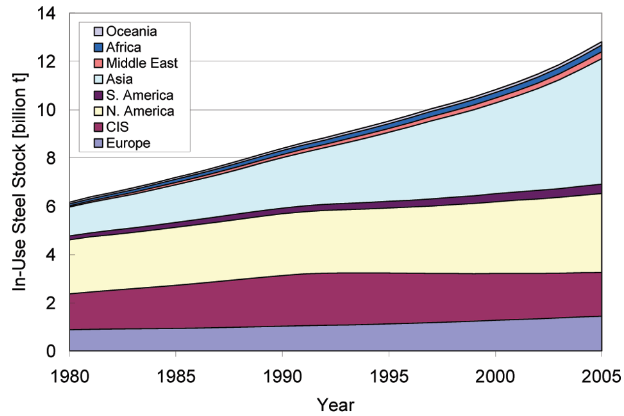

FIGURE 1. In-use stock of steel by region, 1980–2005.

To calibrate the relationship between s_{sat} and population density for civil engineering and building, we conducted dynamic MFA focusing on 47 prefectures in Japan. The MFA offered the in-use stock for respective prefectures, and then s_{sat} values were calculated by nonlinear regression. These 47 s_{sat} values were considered reliable because the per capita steel stock for civil engineering or building in Japan has nearly reached the end of an S-shaped curve. Then, these 47 s_{sat} values were plotted against the data on population density (represented in person/km^2). As a result, the following relationship was obtained for civil engineering ($R^2 = 0.73$).

$$s_{\mathrm{sat}} = 1.25 + \frac{537}{\text{population density} + 131} \tag{13}$$

Civil engineering projects, such as roads, airports, and dams, are indispensable constructions for a country. At the same time, a number of public constructions are not so sensitive to the population. Therefore, the per capita saturation value s_{sat} declined against population growth indicated as eq 13. For building, on the other hand, little apparent correlation is observed. It simply states that in-use stock increases roughly in proportion to the population. The s_{sat} values were scattered in the 4–6 t/capita range; therefore, 5 t/capita was used as a representative value for this and other countries (see Supporting Information for details). In this way, the value s_{sat} in eq 10 was determined exogenously. Then, α and β were determined for each country with nonlinear regression.

For vehicles, Dargay (*26*) characterized the saturation level of vehicle ownership per capita with parameters related to population density and urbanization. We used Dargay's method to forecast vehicle ownership in each country (details of the method are explained in the Supporting Information). In terms of steel weight per vehicle, the average weight for 42 countries in 2005 was calculated by dividing steel consumption for vehicle end uses by vehicle production. This value was adopted and assumed not to change from 2005 to 2050.

Results

World Steel Use in 2005. In order to know how steel flow has been varying in the world until today, our dynamic MFA analyzed the in-use stock and discard of steel in 42 countries by 2005. The results were given by both country and end use and consequently the resource potential of steel was discussed from several perspectives.

Figure 1 shows the in-use stock estimated by region. World steel stock reached 12.7 billion t in 2005, and has doubled

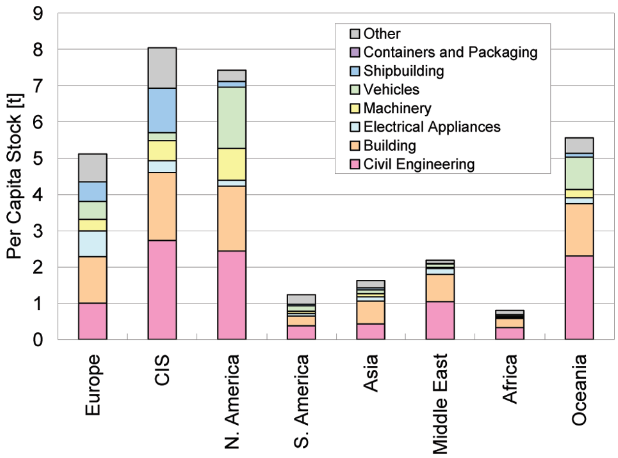

FIGURE 2. Composition of the in-use stock in each region, 2005.

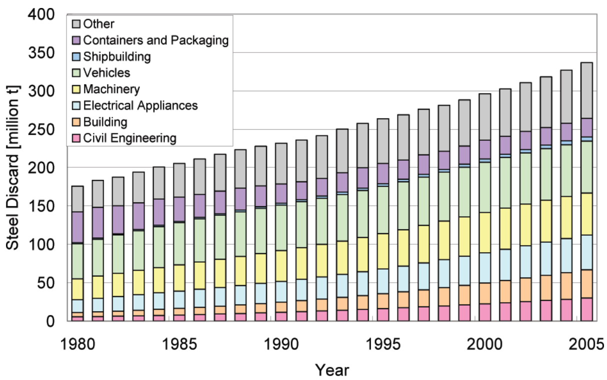

FIGURE 3. Discard of steel by end use, 1980−2005.

in the last 25 years. The growth has been driven by developing Asia, increasing 5 times over the in-use stock of 1980. Africa and South America still do not show a notable increase in their in-use stock. Europe and North America show a slight increase, and CIS decreased their stock because of a depression in steel consumption after the collapse of the Soviet Union. In terms of end uses, civil engineering and building account for 60% of world stock because of their large consumption and long lifetimes. The composition of the in-use stock in each region for 2005 is shown in Figure 2, and is represented as per capita volume. The total in-use stock of 12.7 billion t is equivalent to 2.5 t/capita as the world average. North America and CIS were estimated as having large per capita stock. Because the large steel consumption before the collapse of the Soviet Union remains in existing constructions, it is not surprising that our dynamic MFA provides a large volume of per capita stock for CIS. Nevertheless, there is a possibility of overestimation because the collapse and subsequent disorder may yield accidental abandonment of steel in the society. Per capita stock in Asia was estimated to be 1.6 t on average. Korea (10.2 t/capita) and Japan (9.1 t/capita) had high values, while China (1.8 t/capita) and South Asian countries (0.5 t/capita) were still at a low level. The per capita stock in North America was estimated to be 7.3 t, and 9.1 t in the United States. Compared with Müller's estimation of 12 t/capita (*13*), the values for civil engineering, building, and transportation are similar, but the value for machinery is smaller. Our data provide smaller apparent consumption of finished steel in the 1960s compared with Müller's study; therefore, the different data assembling method might cause the discrepancy.

The amount of steel in end-of-life products reached 340 million t in 2005 (Figure 3), i.e., less than half the steel consumption (840 million t), and the difference between these values represents the growth of in-use stock. Civil engineering and building account for only 20% of the discard because of their long lifetimes, although they account for 60% of in-use stock. The increase in discard from these end uses will be significant in managing the world steel cycle.

The estimations of previous studies are compared with this paper in Table 1. The total stock shows a close value to Kozawa's study (*27*) though the longer lifetimes assumed in this study provide a larger stock. For the United States, a discrepancy is observed between the present study and Müller et al. (*13*). This might be caused by the data assembling method, in which the same lifetimes were used; the discrepancy for the United Kingdom is explained by the same reason. For Japan, the present study estimated larger in-use stock in vehicles, because we used a longer lifetime than Daigo et al. (*29*). The study by Wang et al. (*1*) is one of the few global analyses that discuss both regional and country-level data. Despite their use of the bottom-up approach (except for vehicles), the results show good agreement with ours, which were based on a top-down approach, except for Europe and CIS. The difference regarding Europe was caused by the different number of countries covered in the analysis: 22 countries in Wang's study and 8 countries in this study. Regarding CIS, one of the reasons for the differences was that part of the end-of-life products has remained in the society. Materials contained in these products are called hibernating stock. The hibernating stock is counted as "discard" in the top-down approach because it served out its lifetime, but is not counted as "discard" in the bottom-up approach because it does not appear in the waste streams.

World Steel Use by 2050. Our MFA showed that by 2005 world steel use was driven by civil engineering, building, and vehicles. We therefore estimated the future in-use stock for these end uses using country-specific parameters, and then growth in steel demand was forecasted by 2050 with eq 11. We also estimated the future steel discard by 2050, which is shown in Supporting Information.

Our estimation shows that steel stock for three end uses reaches 55 billion t in 2050, which is 6 times larger than in 2005 (Figure 4). The increase is obviously dominated by developing Asia where the stock increases from 3.7 billion t in 2005 to 36 billion t in 2050. Among the 36 billion t in Asia, China and India have 14 and 13 billion t, respectively. In 2050, the amount of stock in each country is roughly proportional to the population because economic growth of a country leads to saturation of per capita stock. Yet, per capita GDP in some African countries such as Egypt and Nigeria, and Asian countries such as India and the Philippines, will be still lower than $15 000 in 2050, and the stock in these regions is expected to show further increase.

The future of steel input was calculated as shown in Figure 5. To satisfy the in-use stock estimated above, steel demand keeps growing and reaches 1.8 billion t by around 2025. The world steel demand will be obviously driven by developing Asia (Figure 5a). The steel demand in other regions also grows (5-fold demand in 2025 in South America and 10-fold in Africa, compared with 2005 data), yet the impacts are smaller than in Asia. Then, looking at steel demand by end uses (Figure 5b), by 2025, a large part of the steel demand will be consumed in civil engineering and building. Because infrastructures and dwellings are indispensable for living, the demand for these products may grow, with first priority in developing countries. Then, around 2025, there is a slight depression in steel demand. This indicates that steel demand for civil engineering or building in developing countries takes the (local) maximal value around 2025. S-shaped curves have an inflection point, where $\partial^2 s_t/\partial \mathrm{GDP}_t^2 = 0$ at $\mathrm{GDP}_t = \alpha/\beta$ in eq 10 and $-(\ln(-\alpha)/\beta)$ in eq 12. At the inflection point, the net addition to stock $\Delta(I_t - O_t)$ is maximized on a per capita

TABLE 1. Comparison of Estimated In-Use Stocks and Discards with Literature

references	research area	year of estimation	subject estimated (stock/discard)	value in the reference [million t]	value in this study [million t]
Kozawa et al. (*27*)	world	2005	stock	10 000	12 700
Müller et al. (*13*)	USA	2004	stock	3200	2700
Davis et al. (*28*)	U.K.	2001	discard	10	16
Daigo et al. (*29*)	Japan	2000	stock	900	1090
Wang et al. (*1*)	Europe	2000	discard	92	53
	CIS			27	63
	North. America			89	94
	South America			11	12
	Asia			111	114
	Middle East			6.7	6.3
	Africa			5.4	5.4
	Oceania			3.3	4.5

basis. As a result, steel input shows an inverted U-shaped curve against GDP_t under the condition of gradual population change.

Then, after 2025, steel demand for vehicles begins to increase, and decreases for civil engineering and building. Vehicles are important goods for human society but not as basic as infrastructure and dwellings. Therefore, steel consumption for vehicles and other products may rise after infrastructure and buildings spread to some extent. Such an industrial shift is presented in Figure 5b. Afterward, the total steel input in the 2040s is raised again by demand for buildings. This demand is introduced by replacement of buildings. Because we determined the lifetime of buildings in Asia to be about 30 years, the maximal steel input in the middle of the 2020s leads to another peak in the 2050s periodically.

These results present a baseline scenario that shows general trends of global steel use. Still some data and parameters must be examined; for example, product lifetimes, steel weight in future vehicles, saturation level of per capita stock (s_{sat}). In the further work, the uncertainty analyses and the scenario analyses would help to present possible future steel cycle.

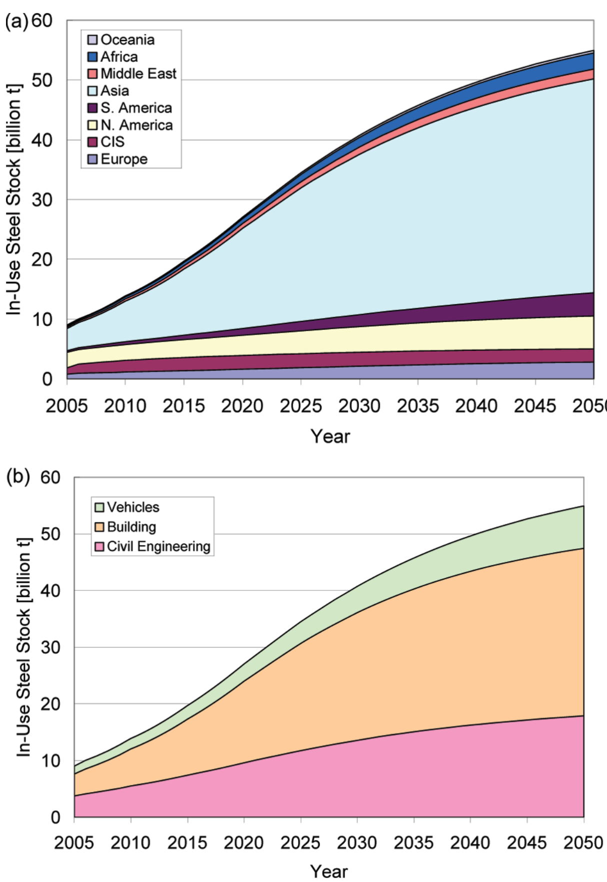

FIGURE 4. Forecast of in-use steel stock by 2050: (a) by region and (b) by end use.

Discussion

This study analyzed the steel stock and flow in the world at country level using dynamic analysis. Material flow, such as input to the society, in-use stock, and discard, were estimated

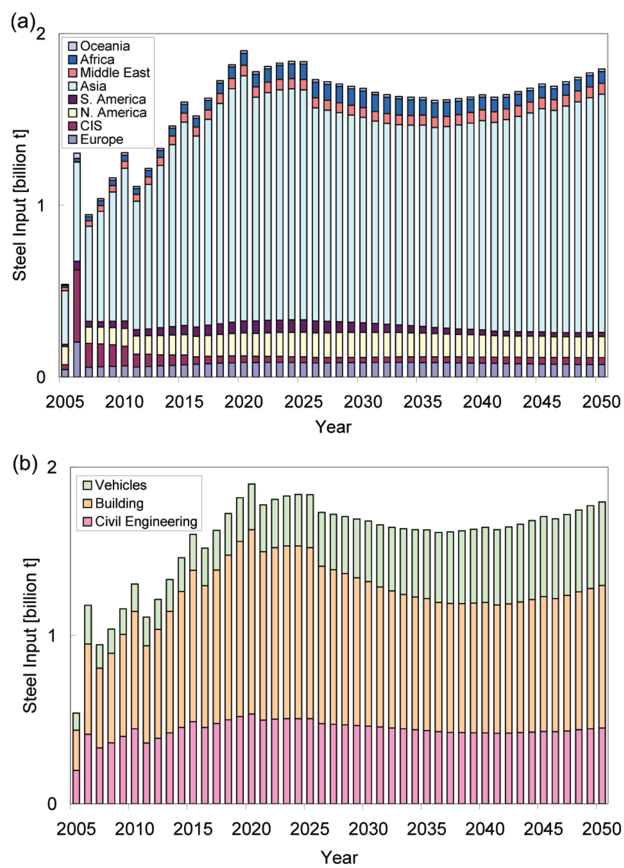

FIGURE 5. Forecast of steel demand by 2050: (a) by region and (b) by end use. Discontinuous points are observed at 2005, 2010, 2020, and 2025. Because the stock before 2005 is estimated with eq 7 and the stock after 2005 with eq 10 and 12, the steel input for 2005 took the irregular value to make up for the divergence caused by different equations. The other discontinuous points are because of the GDP growth scenario. The GDP growth rates were assumed to change at 5-year intervals. This problem would be solved if GDP growth rates would change smoothly.

from 2005 data for 42 countries. These values were compared with the former static analyses and were found to correspond well, although our study employed dynamic analysis. On the basis of these results, the prospects on future steel use were provided. This study is the first attempt to estimate future steel demand by the dynamic MFA, from the point of view that "stocks drive flows". The forecast of in-use stock targeted three major end uses: civil engineering, building, and vehicles, which account for 70% of current in-use stock. Future stock growth was estimated on the basis of past stock increase and was characterized by country-specific social parameters. The results showed that Asia will dominate, with 65% of world steel stock. This estimation simply is attributed to population numbers. From among the 42 countries this study focused on, 60% of the population will be living in Asia in 2050. The steel demand was then calculated from the forecast of the in-use stock. The conversion from stock to demand was based on the material balance shown in eq 2. Because future steel discard must be provided in parallel in this equation, the combination with dynamic analysis was required. The resulting demand is also driven by developing Asian countries. Steel demand in these countries drastically increases at first, then decreases as products spread, and increases again with replacement demand. As a result, steel demand by 2040 draws an inverted U-shaped curve. It is thought that an inverted U-shaped demand curve and an S-shaped stock curve intrinsically include common concepts such as market saturation, technological development, and substitution of other materials. The difference with the IU hypothesis is a resurgence of steel demand that is expected after the inverted U-shaped curve. In the IU hypothesis, replacement demand has not been discussed, or it can be regarded that the resurgence would be canceled by substitution with an advanced material. A quick change in material composition occurs especially in the state of the art products; still, the steel will be the main component of construction products for its strength and low price. The resurgence of steel demand proposed here is a considerable perspective for the design of future steel use.

Worldwide MFA becomes significant as the borderless move of material increases. Country-level MFA provides the supply demand balance, which suggests the transition of the steel trades in the future. One of the recent interests is trade in steel scrap. The trade in scrap causes not only a change in the quantity of scrap in the domestic recycling process, but also a change in the quality of recycled steel (*30*). Material quality is an important concept in assessing material recycling (*14, 31*) because the required quality differs between products. For example, it is hard to recycle steel scrap from buildings into steel plates for vehicles, because of the high concentration of copper. In our forecast, a large amount of steel will be put into civil engineering and building by 2025, which will come to be discarded in the 2040s. To exploit these resources, it is necessary to propose, evaluate, and undertake effective measures, e.g., develop the recycling technology of extracting the contamination, and enhance the building-to-building recycling mechanism. Our dynamic analysis provides a backbone of the model that analyzes these issues in global scale.

The resource potential and the prospects of steel use estimated in this study will become important pieces in the material model that discusses global resource management. Furthermore, energy consumption, CO_2 emission, and other environmental issues in terms of steel industry can be discussed on the basis of the results of this study. However, the "steel model" is not independent from the other materials. The growth in steel demand also increases the zinc consumption for coating. If the use of steel products with copper is enhanced, contamination by copper might disturb steel recycling. It is expected that future studies would develop a model of various materials and integrate them considering their interdependence. Such attempts will lead to modeling of the entire industrial ecology.

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Supporting Information Available

The data resources, parameters used in the dynamic analysis, methodologies of vehicle forecast, and preanalyses on consumption and stock of construction end uses.This material is available free of charge via the Internet at http://pubs.acs.org.

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SUPPORTING INFORMATION

Outlook of the world steel cycle based on the stock and flow dynamics

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Contents of the Supporting Information:

Number of Pages: 9 Number of Tables: 4 Number of Figures: 3

S-1 Research areas

The following countries are discussed in this study. These countries account for 85% of the world steel consumption in 2005.

Table S1. Countries and territories analyzed in this study.

Region	No.	Country
Europe	7 (8)	Belgium–Luxembourg, Germany, Greece, Norway, Spain, Turkey, the United Kingdom
CIS	1	Russia
North America	3	Canada, Mexico, the United States
South America	5	Argentina, Brazil, Colombia, Ecuador, Venezuela
Asia	13	Bangladesh, China, Hong Kong, India, Indonesia, Japan, Korea, Malaysia, Pakistan, Philippines, Singapore, Taiwan, Thailand
Middle East	4	Iran, Kuwait, Saudi Arabia, UAE
Africa	6	Algeria, Egypt, Kenya, Libya, Nigeria, South Africa
Oceania	2	Australia, New Zealand

S-2 Data preparation of steel consumption

The steel statistical yearbook by the World Steel Association (formerly the International Iron and Steel Institute) provides the data on "apparent consumption" for each country. The trade in finished steel, such as plates or bars, is already counted in the values of apparent consumption (*S1*). Therefore, apparent consumption of steel is regarded as "the amount of steel consumed in the domestic fabrication and manufacturing processes".

From the yearbook, we obtained the statistics on apparent consumption after 1974. We estimated the apparent consumption before 1974 as accurately as possible by assuming that the ratio between apparent consumption and crude steel production were the same as in 1974. We traced back the apparent consumption to 1900 for Germany, the United Kingdom, Russia, the United States, and Japan; 1913 for India; 1926 for Brazil; 1949 for China; 1950 for Korea; 1955 for Taiwan; and 1967 for the other countries.

The share of each respective end use was inferred from literature (*S2*) except for Japan and the United States. The data availability is shown in Table S2.

S-3 Data resources for parameters

This study dealt with some social parameters. Populations in respective countries by 2050 were obtained from the United Nations database (*S3*). The data were quinquennial and therefore made up with linear interpolation. Population density of respective countries was calculated by dividing by their land area. GDP data were obtained from the IMF database as constant 1990 PPP $ (*S4*). The GDP growth scenario over 2005–2030 was taken from *International Energy Outlook 2008* published by the U.S. Department of Energy (*S5*), and growth rates over 2030–2050 were set to the same as 2025–2030. The parameter urbanization was taken from *World Development Indicators 2005* by the World Bank (*S6*). The value of urbanization was assumed not to change over time.

Table S2. Availability of data on the share of end uses.

		1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Europe	Bel-Lux				✔		✔								
	Germany			✔											
	Greece				✔		✔			✔	✔				
	Norway						✔			✔					
	Spain				✔		✔			✔					
	Turkey				✔		✔			✔	✔				
	United Kingdom				✔		✔			✔	✔				
CIS	Russia												✔	✔	
N. America	Canada				✔		✔			✔					
	Mexico			✔			✔			✔	✔				
	United States													✔	
S. America	Argentina			✔			✔				✔				
	Brazil			✔		✔				✔	✔				
	Colombia				✔		✔			✔	✔				
	Ecuador				✔		✔								
	Venezuela			✔			✔			✔	✔				
Asia	Bangladesh					✔				✔	✔				
	China						✔			✔			✔		✔
	Hong Kong			✔			✔			✔			✔	✔	✔
	India						✔			✔	✔				
	Indonesia						✔			✔			✔	✔	✔
	Korea			✔	✔					✔			✔		✔
	Malaysia				✔		✔			✔			✔	✔	✔
	Pakistan				✔	✔				✔	✔				
	Philippines				✔		✔			✔			✔	✔	✔
	Singapore				✔		✔			✔			✔	✔	✔
	Taiwan			✔			✔			✔			✔	✔	✔
	Thailand				✔		✔			✔			✔	✔	✔
Middle East	Iran				✔		✔			✔			✔	✔	
	Kuwait				✔		✔			✔	✔				
	Saudi Arabia			✔			✔			✔	✔			✔	
	UAE				✔		✔			✔					
Africa	Algeria			✔			✔								
	Egypt				✔		✔			✔	✔				
	Kenya				✔		✔								
	Libya			✔			✔								
	Nigeria				✔		✔			✔					
	South Africa			✔			✔			✔					
Oceania	Australia			✔			✔			✔		✔			
	New Zealand				✔		✔			✔	✔				

Table S2. (continued)

		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Europe	Bel-Lux												
	Germany							✓					
	Greece												
	Norway												
	Spain												
	Turkey		✔		✔			✓					
	United Kingdom		✔		✔			✔					
CIS	Russia		✔		✔				✔				✔
M. America	Canada		✔		✔			✔				✔	
	Mexico		✔		✔			✔					
	United States		✔		✔				✔				
S. America	Argentina												
	Brazil		✔		✔				✔				
	Colombia												
	Ecuador												
	Venezuela												
Asia	Bangladesh												
	China		✔		✔			✔					
	Hong Kong			✔	✔			✔					
	India			✔	✔				✔			✔	
	Indonesia			✔	✔			✔				✔	
	Korea		✔		✔				✔			✔	
	Malaysia		✔		✔			✔				✔	
	Pakistan												
	Philippines			✔	✔				✔				
	Singapore			✔	✔			✔				✔	
	Taiwan		✔		✔				✔				
	Thailand		✔		✔			✔				✔	
Middle East	Iran												
	Kuwait												
	Saudi Arabia				✔			✔					
	UAE												
Africa	Algeria												
	Egypt												
	Kenya												
	Libya												
	Nigeria												
	South Africa												
Oceania	Australia			✔	✔			✔				✔	
	New Zealand												

S-4 Estimation on the consumption for civil engineering and building

Steel is an abundant and durable metal; therefore, it is used as constructional material. Construction has been, and probably will continue to be, the largest use for steel. The objects included in “construction” can be categorized into two end uses: civil engineering and building. The end use “civil engineering” indicates the infrastructural objects by public works: dams, water and sewerage facilities, roads, airports, etc. The end use “building” indicates the constructions for residential or commercial use: houses, offices, educational or cultural facilities, etc. These two are hardly distinguished in the previous dynamic MFA. However, the future steel use in these end uses shows different behaviors against the social parameters (detailed analysis is described in S-8). To take into account the different behaviors in our forecast, the steel consumption for construction was allocated into the two end uses in our dynamic MFA.

In the allocation, we used the parameter CEP, which represents the civil engineering portion.

$$CEP = \frac{Consumption\ \ for\ civil\ engineering}{Consumption\ \ for\ construction} = \frac{Consumption\ \ for\ civil\ engineering}{Consumption\ \ for\ civil\ engineering\ and\ building} \tag{S1}$$

We presumed that CEP is small where population density is high because steel requirement for building would be sensitive to the population compared with civil engineering. The relationship between CEP and population density (represented in person/km^2) was verified using data on 47 prefectures in Japan (*S7*).

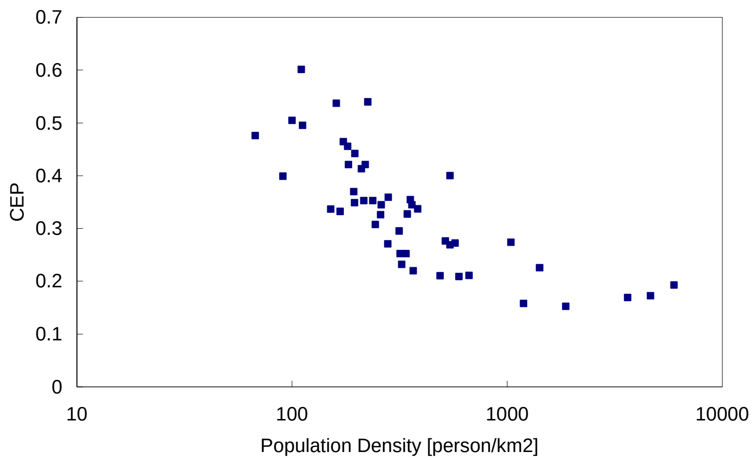

FIGURE S1. CEP against the population density in 47 prefectures in Japan, 2005.

The result (Figure S1) provides the following relationship (R^2 = 0.68).

$$CEP = 0.191 + 0.419 \times exp(-\frac{Population\ Density}{276}) \tag{S2}$$

Using eq S2, the CEP in each country was calculated for every year. Then, time-series steel consumption for civil engineering and building were calculated respectively in 42 countries.

S-5 Yield losses in the fabrication and manufacturing processes

We determined the yield ratios as in Table S3, which was estimated from the survey in Japan (*S8*).

Table S3. Yield ratios for respective end uses.

End use	Yield ratio
Civil engineering	0.94
Building	0.94
Electrical Appliances	0.81
Machinery	0.86
Vehicles	0.81
Shipbuilding	0.93
Containers and Packaging	0.92
Other	0.95

S-6 Indirect trade in steel

In this study, we estimated the indirect trade as follows. Steel products used in civil engineering or building are immovable constructional material, and thus we assumed that there is no indirect trade for these end uses. For vehicles, the indirect trades of steel were calculated as a product of the traded number of vehicles and steel weight per vehicle. The traded number of vehicles was calculated from vehicle production and new registrations (*S9*), and steel weight was estimated as a global average, not depending on vehicle type, from the amount of steel consumption for vehicles and the number of vehicles produced in 42 countries. For the other end uses, the indirect trade of steel was not considered due to the problem of data availability.

S-7 Product lifetimes used in the dynamic MFA

Table S4. Average lifetimes used in this study.

(unit: year)

	Europe CIS Africa	North America South America	Asia Middle East Oceania		
			Japan	China	The rest
Civil engineering	60	75	34.5	32.5	33.5
Building	60	75	28.9	32.5	30.7
Electrical Appliances	16	15	12.1	21.5	16.8
Machinery	15	30	12.1	17.5	14.8
Vehicles	13	20	13	17	15
Shipbuilding	60	60	60	60	60
Containers and Packaging	Discarded in the year of production.				
Other	25	15	12.1	10	11.1
(References)	(*S10*)	(*S11–12*)	(*S13-14*)	(*S15*)	

* Average lifetime of "shipbuilding" was obtained from Melo's study (*S16*) and used in all regions.
** Average lifetime in "The rest" was set to the mean value of Japan and China.
*** The Weibull distribution (shape parameter 3.5) was used for the distribution function.

S-8 Determination of s_{sat} for civil engineering and building by population density

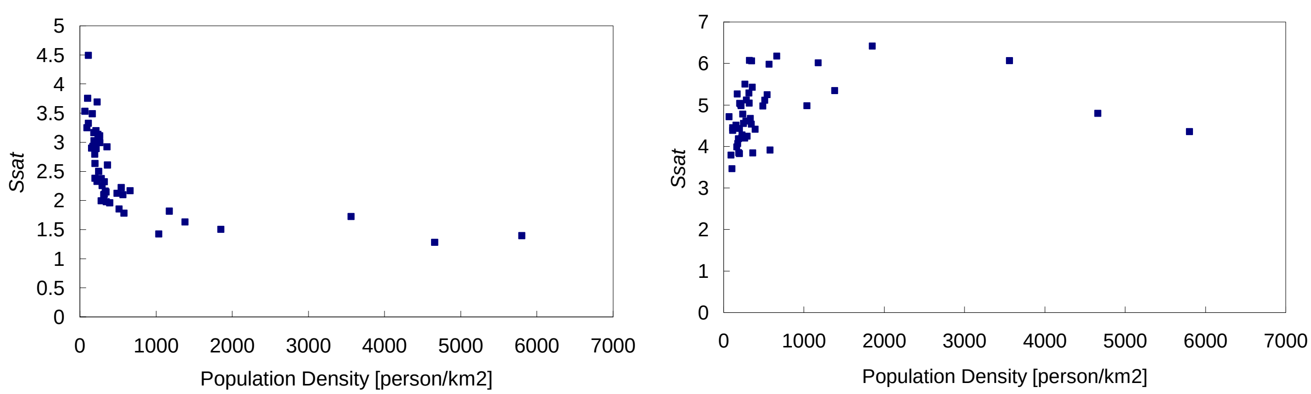

FIGURE S2. The relationship between s_{sat} and population density.
(left panel) civil engineering (right panel) building

We conducted the MFA of steel in civil engineering and building end use focusing on all 47 prefectures in Japan. The value s_{sat} for each prefecture was calculated from time-series data on per capita in-use stock, by fitting the increase into eq 10 with nonlinear regression. The 47 s_{sat} values obtained were plotted in Figure S2 against population density. From Figure S2, we expressed the relationship between s_{sat} and population density as eq 13 for civil engineering and s_{sat} = 5, which is independent of population density, for building. The relation was used to determine the s_{sat} values for 42 countries by 2050. For some countries, however, the estimated per capita stock in 2005 has already surpassed the s_{sat} provided by the foregoing relationship. For these cases, the in-use stock grows to a satisfactory extent; therefore, we adopted s_{sat}, which was determined with nonlinear regression. The determination of parameters s_{sat}, α, and β is summarized as follows. For most countries, s_{sat} is estimated first exogenously by a foregoing relationship, and then α and β are determined to minimize the least square against historical per capita stock growth. When the estimated s_{sat} is inappropriate, the three parameters are determined to minimize the least square against historical per capita stock growth. The latter case is applied to the countries/territories below.

Civil engineering: Hong Kong, Taiwan, Singapore, and Kuwait

Building: Hong Kong, Taiwan, Korea, and Singapore

S-9 Characterization of s_{sat} for vehicle ownership (based on Dargay's method)

Dargay et al. (*S17*) determines the per capita vehicle ownership in year *t* with eq 12.

$$s_t = s_{sat} \exp(\alpha \exp(\beta \times GDP_t)) \tag{S3}$$

The saturation value s_{sat} in eq 12 is determined as eq S4.

$$s_{sat} = 0.85 + \lambda \overline{D} + \phi \overline{U} \tag{S4}$$

where λ and ϕ are coefficients, and $\overline{D}$ and $\overline{U}$ are defined as follows.

$$\begin{aligned} \overline{D} &= D_{j,t} - D_{USA,t} \quad \mathit{if} \quad D_{j,t} > D_{USA,t} \\ &= 0 \quad \mathit{otherwise} \end{aligned}$$

and

$$\begin{aligned} \overline{U} &= U_{j,t} - U_{USA,t} \quad \mathit{if} \quad U_{j,t} > U_{USA,t} \\ &= 0 \quad \mathit{otherwise} \end{aligned}$$

$D_{j,t}$ and $U_{j,t}$ respectively denote the population density and urbanization in country *j* at time *t*. Coefficients λ, ϕ and parameters α, β are determined by nonlinear regression (see Dargay's original paper for details). The original paper dealt with the GDP on a constant 1995 PPP $ basis. Our study dealt with the GDP on a constant 1990 PPP $ basis; therefore, we adjusted the parameter β for the respective countries provided by Dargay et al.

S-10 Estimation on future steel discard

Steel discard from three end uses (civil engineering, building and vehicles) was estimated by 2050 as Figures S3-1 and S3-2. Steel discard is estimated as 135 million t in 2005 and 1,460 million t in 2050, while steel demand is estimated as 540 million t in 2005 and 1,800 million t in 2050 (see Figure 5). Discard in Asia will increase considerably and discard in developed countries will also increase due to the increase in scrap from civil engineering and building.

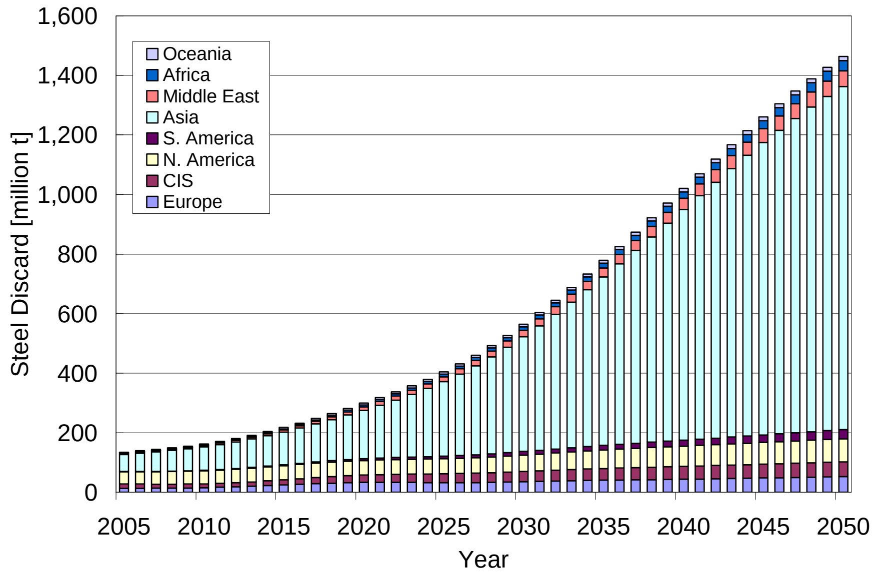

FIGURE S3-1. Discard of steel by region, 2005-2050.

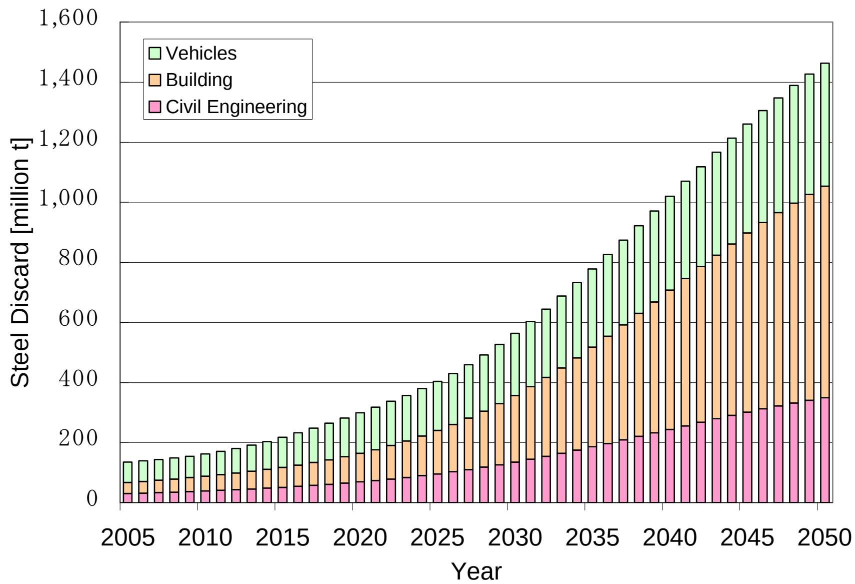

FIGURE S3-2. Discard of steel by end use, 2005-2050.

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