



# Improving material projections in Integrated Assessment Models: The use of a stock-based versus a flow-based approach for the iron and steel industry



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## ABSTRACT

The steel industry is responsible for a large share of the industrial energy consumption and greenhouse gas emissions and several long-term energy models have some representation of this sub-sector. It is found that models, commonly use a flow-based approach for projecting steel demand neglecting that in-use steel stocks serve as a better demand indicator than steel consumption. A stock-based method that uses the historical steel stock results from detailed material flow analysis is developed for making steel demand projections and implemented in the IMAGE Integrated Assessment Model. Large differences between the two approaches arise. For the first half of the 21st century, global steel demand increases with both approaches and at a similar rate to reach 2300 Mt/yr by 2050. For the second half of the 21st century, however, the developments differ drastically. With the stock-based approach, global steel demand decreases by 0.8%/a to reach 1600 Mt/yr, while with the flow-based approach it increases by 0.3%/a to reach 2600 Mt/yr in 2100. Given that steel production levels have a profound contribution to greenhouse gas emissions, using the right approach is crucial. This means that long-term energy models may currently overestimate the industrial emissions in the last half of the century.

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## 1. Introduction

In 2017, global steel production exceeded 1600 Mtonnes (Mt); that is more than double the amount of steel produced in 1980 [1]. The increased steel demand resulted in increased energy consumption and Greenhouse Gas (GHG) emissions. In 2017, total energy use for steel making (incl. energy use in coke ovens and blast furnaces) reached 33 EJ<sup>1</sup> (21% of global industrial energy use) ranking it as the second largest energy using industrial sub-sector [2]. Iron and steel production is expected to increase in the future in order to meet the increasing demand for steel, especially in the developing countries. Incremental changes in current steel production processes with the adoption of currently available

technologies would not be enough to meet the emission goals [3], with innovative technologies (e.g. hydrogen-based, switch to electrified processes) having to be widely adopted to decarbonize this industry.

Following the industry's important role in energy consumption [2], some Integrated Assessment Models (IAMs) represented iron and steel as a separate industrial sector. IAMs are used to generate global or regional scenarios on energy use, GHG emissions, climate and other issues by combining knowledge from different disciplines. They are widely used in climate change assessments, such as the IPCC Synthesis report [4], the Global Energy Assessment (GEA) [5], the OECD environmental Outlook [6], and the Global Environmental Outlook [7]. IAMs describe both the energy demand and the energy supply systems. Given the difficulties in describing the heterogeneous activities and technologies associated with the energy demand side, IAMs traditionally had much more detail in terms of energy supply than energy demand. Over time, however,

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most IAMs have started to include more demand detail. Still, there are large differences in the way these models deal with energy demand, which also leads to diverging model results [8]. Determining the right level of detail in energy demand represents an important dilemma for the global and long-term IAMs: while on the one hand, including demand-side details increases policy-relevance and possibly the representation of relevant sub-sector dynamics, on the other hand, IAMs also need to simplify the systems they represent for reasons of transparency and uncertainty.

In this article, the representation of steel-demand projections in IAMs and the options for improvement is discussed. Understanding and capturing the drivers of material demand and its saturation level is of crucial importance for long-term projections used in the evaluation of scenarios for achieving climate goals [9], as it affects all GHG mitigation scenarios that need to be evaluated. Ideally, total demand would be coupled to separate steel demand for construction, automotive and machinery sectors in both developing and industrialized countries. It is argued that in-use steel stocks (i.e., the steel contained in products that are in-use in a given year) instead of annual steel flows can better indicate the services that steel provides in an economy [11] and therefore would be a better predictor of future steel demand [10]. Increasing population, industrialization and urbanization are currently the main drivers of steel demand and when growth in these drivers come to a halt, steel consumption drops [12].

There are two main advantages of such a stock-based approach. The first is that such an approach considers the demand for services that steel-containing products offer. This would allow modelling material demand more realistically through reduced demand for services, or through substitution of materials or function. This would make IAMs more relevant in assessing circular economy policies and strategies [13]. The second is that with such an approach, also using the age distribution of the in-use steel stock, the amount of retired steel can be calculated, which can be used to produce steel from post-consumer scrap. This allows for more accurate forecasting of the different routes (each with distinctively different energy use) for steel production and results in improved modelling of the total energy use and GHG emissions.

The flow approach is currently the more common approach used in IAMs to model steel demand, where steel consumption is directly correlated with income levels. In Ref. [14] steel and alloy demand, and in Ref. [15] the overall industrial energy intensity are correlated to the income level. In other studies, the Japanese steel demand [16], the world steel demand in the ISIM model [17], the steel demand in 26 different regions in the TIMER model [18], the global steel demand [19], the Chinese demand for a variety of industrial products among which the demand for steel [20], and the steel and cement demand in IMAGE [21] are also linked to the income level. These relationships can be derived from the historical correlation of per capita Gross Domestic Product (GDP) with steel use intensity (defined as steel consumption in kg per GDP). These two variables are typically assumed to be related to each other through an inverted U-shaped curve, where steel use intensity becomes decoupled from GDP per capita growth at higher values [14]. Alternatively, an S-shaped curve is used in some studies to relate steel consumption per capita and GDP [22], building materials and GDP [23], and steel and cement demand and GDP [21,24]. As a third alternative, and mostly for short-term projections, extrapolations of past growth rates can be used, such as in a model for the Chinese industry [25], and in a European steel model [26].

There are several studies that analyze current and possible future developments of accumulated in-use steel stocks. Using a top down approach, steel stocks were estimated for Japan [27] and for a Chinese province [28]. Material Flow Analysis (MFA) was used

to estimate the steel stock build-up and scrap availability in the Chinese residential sector [29], and in the different Korean activity sectors (construction, transportation, machineries and electrical devices) up to 2020 [30]. More recently, the future material needs and material stocks, including steel, in the residential and service buildings in 26 regions was estimated up to 2050 [31] and the future metal demand and stocks in power generation technologies [32] were estimated using MFA. In another study, the impact of increased electricity consumption on the metal needs for the manufacture of the components used in power generation technologies has been assessed [33], while in Ref. [34] the metal needs up to 2050 for electricity generation and transport vehicles. An MFA analysis was also used to estimate steel stocks in the EU27 from 1945 to 2013 [35] and to estimate steel stocks in 200 countries for the period 1700–2008 [10]. Scenario analyses were performed for the future iron in-use stocks in China [36], with the future steel demand in China based on the analysis of future product stocks (floor space, vehicles, household appliances etc.) [37], using both material flow dynamics and market dynamics (e.g., resource prices, capacity planning) to estimate future Chinese steel demand [38,39]. Using the same concept, “stocks drive flows” [40], future steel stocks and steel demand were estimated for 42 countries [41], for China [42] and for ten world regions [43] up to 2100. The studies suggest that in-use steel stocks in all economies will saturate after they reach a certain level, and this will have an impact on the demand for new steel.

However, the practical application of a stock-based steel demand modelling approach is limited in IAMs, the main reason being the lack of stock data. With IAM projections continuing to rely on steel flows, the importance of material cycles is overlooked, with the links between economic activities and material use (the true driver of material demand) and recycling potentials not accurately captured [44]. In combination with the underrepresentation of the industry sector and the different industrial processes in long-term energy models [8], the material efficiency potentials, although significant [45,46], are to a great extent insufficiently captured [47]. Linking industrial ecology studies, devoted in analyzing material cycles, to IAMs, could thereby be the way to more robust evaluation of model scenarios [44] without substantially increasing the complexity (e.g., by gathering and linking trade, production and manufacture data) of IAMs.

In this study, the IAM state of the art modelling is initially investigated. In a next step, how a steel stock approach can be applied to an IAM model based on the available data is examined, and the impact this new approach will have on models results is assessed. For this, the stock data from Ref. [10] are used to estimate the future steel stock build-up that is then used in the IMAGE Integrated Assessment Model to estimate future steel consumption. The steel demand projections in IMAGE based on the original, flow-based steel approach [21], are then compared to the new projections based on the stock-based approach. In so doing, essentially a comparison is made of a method based on the saturation of per capita consumption to a method based on the saturation of per capita stocks while using the same GDP and population drivers to better understand how the different methodological approaches impact the projected development of the steel sector.

This article is structured as follows. Section 2 gives an overview of how steel demand or the energy consumption for steel making and the scrap availability are modelled in several IAMs. Section 3 presents a method on how to make steel consumption projections based on the stock analysis in the IMAGE model and Section 4 presents the different modelling results. Finally, Section 5 discussed the results and Section 6 draws the main conclusions.

## 2. Overview of iron/steel sector representation in IAMs

Energy system models vary in the way they represent the industrial sector. A detailed Table in supplementary material (S1) gives an overview on how leading energy models<sup>1</sup> account for two important parameters in steel modelling 1) steel demand/consumption and 2) steel recycling/scrap availability.

Out of the twelve models, seven have a representation of the iron and steel industry (POLES, WEM, ETSAP-TIAM, IMAGE, AIM-CGE, DNE21+ and GCAM). In the rest, the iron and steel sector is part of a more aggregate cluster; in MESSAGE it is part of the whole industry, in GEM-E3 part of the ferrous metals industry, in REMIND part of a so-called stationary sector that also includes the residential and commercial sectors, in WITCH part of the non-electric sector that also includes transportation and residential sectors, and in Imaclim-R part of the energy-intensive industrial sector.

Physical steel demand is accounted for in all models that have an explicit iron and steel industry representation except for AIM-CGE and GCAM. In AIM-CGE, the steel demand is represented in monetary units, and in GCAM it is indirectly accounted for as a part of a single category of homogeneous industrial good. In POLES, ETSAP-TIAM, IMAGE and DNE21+ the steel demand is coupled to the per capita economic activity. This is commonly done by a relationship between steel intensity (annual steel consumption per capita) and economic activity (GDP per capita) based on historical data. Based on this relationship, future annual demand trajectories/developments and saturation levels are determined for each region. In WEM, although additional parameters are considered, such as industry value added and end-use energy prices, it is unclear from available documentation what their exact role is. The models without an explicit representation of the steel industry relate industrial energy demand directly to economic growth.

Steel recycling is considered by three models: IMAGE, WEM and DNE21+. In IMAGE, the use of steel production processes that use scrap as an input is limited by the availability of steel scrap and product quality requirements. A scrap model identifies all the steel flows in an economy and all sources of scrap, divided into circulating (also known as forming scrap), prompt (also known as fabrication scrap) and obsolete (also known as end-of-life scrap) scrap [18]. Although the steel stock built-up is assessed, it is not used as an indicator of steel services, and thereby not used to determine the steel demand. In WEM, a material flow model is used to assist estimations on the level of material efficiency and future steel demand and scrap availability (semi-manufacturing, manufacturing and post-consumer scrap) projections [48] built upon other research on steels stocks. The material flow analysis in WEM has a dual purpose: 1) to estimate scrap availability, and 2) to help estimate future steel demand. In DNE 21+, the share of the secondary route (using primarily steel scrap as input) is set to range between fixed minimum and maximum limits based on exogenously determined scrap availability.

Although not a part of ETSAP-TIAM, a scrap availability model (SAAM) is used in combination with the ETSAP-TIAM model to estimate future steel demand, with scrap availability based on the residence time of steel products in the various activity sectors and steel production technology choices [49]. One of the steel demand scenarios developed, reflects assumptions on the per capita in-use steel stock saturation levels per activity sector from an MFA [10].

### 2.1. Iron/steel sector representation in IMAGE

In this subsection it is shown how the steel demand and scrap availability are modelled in IMAGE.

#### 2.1.1. Steel demand projections in IMAGE

To make long-term steel projections, the steel consumption is linked to the economic activity based on a non-linear function, where material demand decreases over time due to material efficiency improvements. The per capita steel consumption in year  $t$  ( $PCC_t$ ) is calculated from Eq. (1) [21]:

$$PCC_t = a * e^{\frac{b}{GDP_{PCt}}} * (1 - m)^{(t-2010)} + \left( \Delta_{2010} - \Delta_{2010} * e^{-\varphi * e^{-\mu * (t-2005)}} \right) \quad (1)$$

where,  $GDP_{PCt}$  is the per capita GDP in year  $t$ , the parameters  $a$  and  $b$  are parameters estimated based on the regression analysis of historic data,  $\Delta_{2010}$  is the deviation between the actual and estimated steel consumption in 2010, and  $\mu$  and  $\varphi$  are Gompertz parameters with the fixed values of 9 and 0.1, respectively, that remove the demand variations over a 50-year period. Parameter  $m$  is the per year material efficiency improvement with a fixed value of 1%.

#### 2.1.2. Scrap availability projections in IMAGE

IMAGE uses the scrap model to identify the future scrap generated from: i) activities used to produce the metal itself (circulating scrap), ii) activities used in the manufacture of different products (prompt scrap), and iii) the retirement of steel products that reached the end of their lifetime (obsolete scrap). It is assumed that all circulating scrap is almost entirely recycled, while the recycling rate for prompt scrap is 70%. The average obsolete scrap recycling rate is also 70%. The circulating and prompt scrap availability depend on the annual metal and steel containing production activities while obsolete scrap depends on the past consumption of steel containing products. To determine the availability of obsolete scrap, a material flow model is used that is based on past steel consumption in four activity segments (namely construction, machinery, cars and cans) and the average product lifetimes of the four activity segments. The average lifetimes and activity shares are assumed to remain fixed with time (see Table 1). For more information on the scrap model see Ref. [18].

It needs to be noted that to account for the required steel quality for certain applications, the share of scrap use in total steel production cannot exceed 90% [21].

## 3. A steel stock-based consumption model

This section presents a method for projecting steel demand based on the insights from stock analysis. Section 3.1 discusses an approach for projecting steel stocks based on available historical steel stock data. Section 3.2 discusses how the steel stocks that retire annually can be projected based on residence times, and finally Section 3.3, indicates how future steel demand can be projected.

Although the IMAGE model already makes estimates that could be partially used in this analysis, i.e., on historical steel stocks and future steel scrap availability, these were not used in this analysis. This is because we aimed at developing a method that uses data available from literature which can be applied by all energy models.

### 3.1. Method for projecting steel stocks

To estimate future steel stocks for the 26 regions used in the

<sup>1</sup> Selected from the EU ADVANCE project, described at: <http://www.fp7-advance.eu>.

**Table 1**

Default average lifetimes (normal lifetime distributions) and activity shares per activity segment in IMAGE [18].

	construction	machinery	cars	cans
Average lifetime (in years)	70	20	15	5
Standard deviation of lifetime distribution	30	7	5	3
Activity share	35%	25%	25%	15%

IMAGE model, a two-step regression analysis is performed. First for all OECD countries, and then for all 26 IMAGE regions. The first regression analysis has been solely performed to identify the function that better describes steel stock developments. The steps followed are:

- 1) Regress historical per capita steel stocks (dependent variable) against country income levels (expressed in GDP/capita) (independent variable) using data from all OECD countries for the period 1900 to 2008.

To describe stock developments, a variety of functions have been used in literature, either relating material stocks to time, such as in Ref. [50] where Japanese iron stocks are linked to time, and in Ref. [43] where iron and steel stocks in the main world regions are linked to time, or to GDP/capita [41]. Given that economic growth and the development of steel sector are closely related, and that economic growth is a commonly used model driver, the approach linked to GDP was adopted. The per country and per sub-sector steel stock data were taken from Ref. [10], and the population<sup>2</sup> and income data<sup>4</sup> (in real GDP/capita) from Ref. [51]. Several function types were evaluated in SPSS, namely linearized functions, and non-linear S-shaped functions. The best fit was found (based on the std. deviation) with the S-shaped function:

$$S_t(t) = \frac{S_{sat}}{1 + e^{\left(a - b \cdot \frac{GDP(t)}{capita}\right)}} \quad (2)$$

where  $S_t$  is the per capita steel stock in year  $t$ ,  $S_{sat}$  is the per capita saturation level of in-use steel stocks (limit of growth) and  $a$  and  $b$  are constants to be defined in the regression with the constant  $b$  specifying the width or the steepness of the curve. At low incomes there is an exponential growth of steel stocks until a certain income is reached. After that, the growth is restricted until it reaches the upper asymptote. Hence, the total curve describes a typical sigmoid or S-shaped curve.

Fig. 1 shows the historical per capita in-use stocks and GDP for the four activity sectors in OECD countries. The black dotted line shows the results when the regression is performed with the data from all OECD countries together (total OECD). Table 2 reports the  $R^2$  and the standard deviation values (RMSE) for the regressions for the total OECD data. Table 3 shows the range in the saturation levels resulting from the separate regression for each OECD country.

Although there is a strong correlation between GDP and material demand, with the relationship between GDP and the demand for materials (and stocks) being bi-directional<sup>4</sup> [52], to stay close to the approach used by energy models the simplification is made that GDP drives the stocks and not vice-versa.

<sup>2</sup> For the period 1900–1960 the population data are reported in 10-year intervals. The data for the intermediate years were estimated with the use of polynomial interpolation (spline interpolation).

<sup>3</sup> Although in this analysis the use of GDP<sub>ppp</sub> values would be preferable, GDP real values were used instead due to the poor data availability prior to 1970.

<sup>4</sup> i.e. GDP being a driver for material consumption but also the opposite, material consumption being a driver for GDP.

- 2) Aggregate the historical country and sectoral data on steel stocks from Ref. [10] to the 26 regions used in the IMAGE model; and
- 3) Perform a second regression analysis by using the S-shaped curve (Eq. (2)) for all 26 regions and for all activity sectors (transportation, machinery, construction and others).

Future GDP/capita projections were taken from the ssp baseline scenario in IMAGE [53] which are based on [54]. For some developing regions, with economies at early stages of development, and a very low in-use steel stock accumulation, the regression analysis using Eq. (2) is not able to yield meaningful results (e.g., very high or very low  $S_{sat}$ , that is not comparable to the saturation levels identified for OECD countries and shown in Table 3). To solve this, the second regression analysis is run, for these regions, with the constraint that the  $S_{sat}$  should be between the ranges in Table 2. The regression analysis results are available in the supplementary material (S2).

The data regressed in step 1) included only mature economies because their economic structure has changed a lot during the different stages of economic development. Thereby, identifying the relationship between the per capita in-use steel stock and GDP during the different stages of OECD countries' maturing is possible, as opposed to the countries with economies in the first stages of development. However, the main assumption here is that when such a relationship is used in step 3), all developing countries that are currently low in accumulated steel stocks, will follow the same historical trends.

### 3.2. Method for projecting retired steel

Little reliable information is available on steel product lifetimes [11]. In general, steel used in construction takes the longest to retire (35–100 years) with buildings retiring sooner than other structures such as bridges, airports and harbors. Next, is steel used in transportation (6–35 years), with passenger cars typically retiring sooner than buses, trucks, trains, aircrafts and ships. The machineries and other activity sectors encompass heterogeneous mixes of goods. Average lifetimes for machines range between 5 and 37 years, with ICT-related machines having an average lifetime of 5–8 years and machines used in industrial manufacturing typically lasting more than 10 and up to 37 years. Other appliances such as household appliances and packaging have a shorter lifetime (5–14 years), although their lifetime was longer in the 1990's [55].

To estimate the annual retirement rate  $f(x)$ , the historical retired steel volumes on a country level from Ref. [10] are used where they are aggregated to the 26 regions used in IMAGE and fitted to the sigmoid curve, Eq. (3):

$$f(x) = \frac{1}{1 + e^{-k(x-x_0)}} \quad (3)$$

where,  $x_0$  is the mid-point of the sigmoid. It represents the year at which 50% of the steel consumption in year 1 is retired (equal to the average lifetime shown in Table 3) and the constant  $k$  is the logistic growth rate or steepness of the curve.

The analysis results in different retirement rates and average



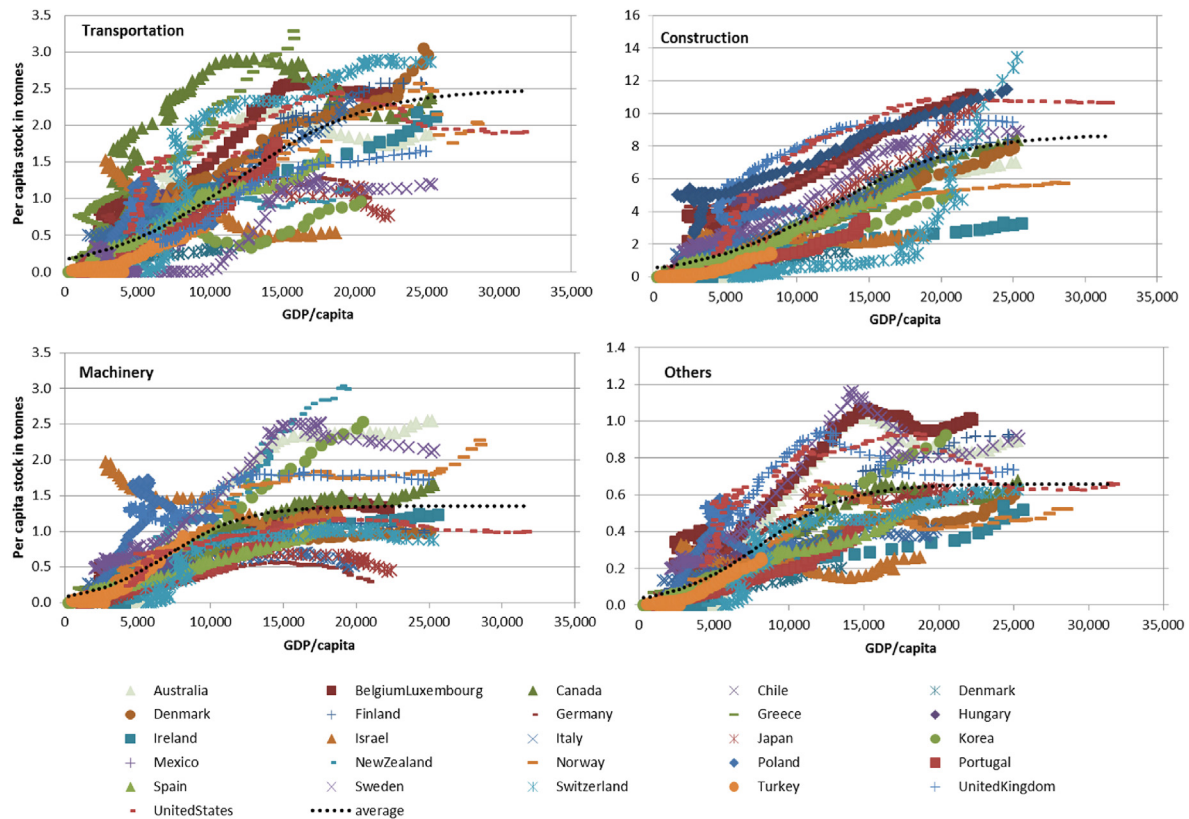


Fig. 1. Per capita historical in-use steel stocks in OECD countries a) transportation, b) machinery, c) construction, and d) others (constructed based on modelled steel stock [10]).

Table 2

S-shaped regression model results for the total OECD country data for the period 1900–2008.

Activity sector	Transportation	Construction	Machinery	Others	Total
$S_{sat}$ (tonnes/capita)	2.52	8.75	1.35	0.66	12.28
$a$	2.64	2.73	2.66	2.79	2.61
$b$	0.000221	0.000221	0.000375	0.000344	0.000252
$R^2$	0.61	0.66	0.58	0.66	0.75
Std. deviation (RMSE)	0.49	1.69	0.39	0.16	2.1

Table 3

Steel stock saturation levels and income levels identified with the regression analysis for the OECD countries.

	Range saturation level (tonnes/capita)	Average Income level (GDP/capita)
Transportation	0.9–2.5	~19,000
Construction	5.6–12	~20,000
Machinery	0.5–2.4	~13,000
Others	0.4–0.9	~14,000

product lifetimes for each sector for all 26 regions. Based on how fast steel is retired, three distinct groups were observed, “Long lifetime”, “Medium lifetime”, and “Short lifetime”, and all countries are assigned into one of these groups. Table 4 shows for each group (“Long”, “Medium”, and “Short”) and sector, the parameters of Eq. (3). The supplementary material (S3) shows the group to which each region is assigned for all four activity sectors and presents evidence from the literature of product lifetime deviations between regions.

The curves in Fig. 2 show the rates at which steel is retired per group and sector up to 2100. For example, in the case of the transportation sector, and for the group Short lifetime, if in year  $t$

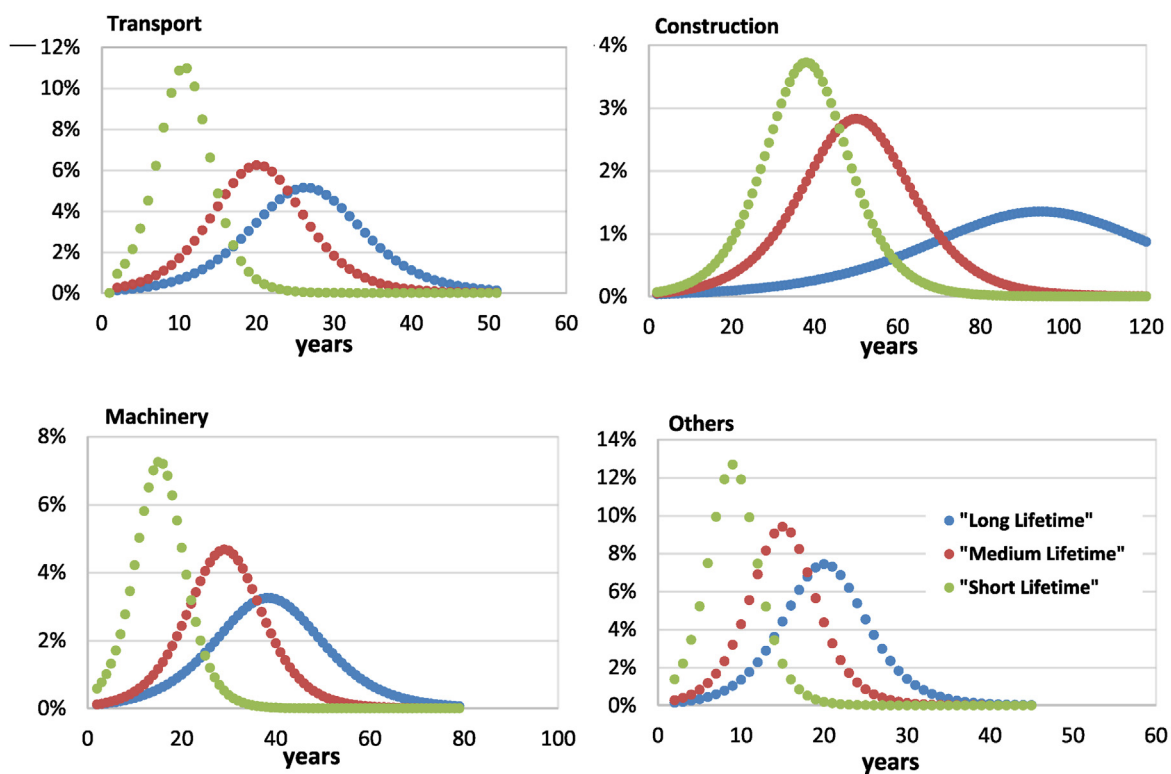
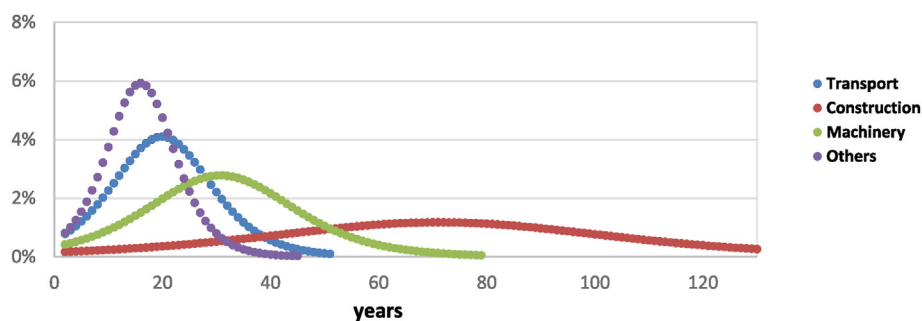
10 Mt enter the in-use steel stocks, in year  $t + 5$  about 3.5% of the steel will retire (0.35 Mt), in year  $t + 10$  about 11% of the steel will retire (1.1 Mt), and so on. It will take 20 years for practically all steel from that age-cohort to retire. This is represented by the integral (the area below the curve).

Although it is important to capture the past retirement patterns to estimate current levels of concentrated in-use steel stocks, it is uncertain whether these patterns will continue. Steel stock lifetime is a critical parameter in the dynamic relationship between retired steel stock and steel consumption. Therefore, a sensitivity analysis is performed where the retired steel and annual consumption is estimated for five scenarios:

**Table 4**

Eq. (3) parameters from the regression analysis.

		Long lifetime	Medium lifetime	Short lifetime	Average lifetime (used in the convergence scenario)
Transportation	$X_0$ (tonnes/capita)	26	20	10	19
	$K$	0.206	0.250	0.444	0.164
	$R^2$	0.99	0.99	0.96	0.77
	Std. deviation	0.03	0.03	0.06	0.19
Construction	$X_0$ (tonnes/capita)	94	50	38	71
	$K$	0.054	0.113	0.149	0.047
	$R^2$	0.85	—	—	0.49
	Std. deviation	0.07	0.1	0.1	0.26
Machinery	$X_0$ (tonnes/capita)	39	30	16	31
	$K$	0.130	0.187	0.291	0.111
	$R^2$	0.98	—	0.97	0.81
	Std. deviation	0.20	0.1	0.17	0.18
Others	$X_0$ (tonnes/capita)	20	15	8	15
	$K$	0.298	0.377	0.510	0.237
	$R^2$	0.93	—	0.89	0.73
	Std. deviation	0.30	0.1	0.40	0.21

**Fig. 2.** Fraction of retired steel (y-axis) in the years after consumption (percent of steel retired per year) in the four activity sectors.**Fig. 3.** Fraction of of steel retired per year (y-axis) in the four activity sectors ("Converging Lifetimes").

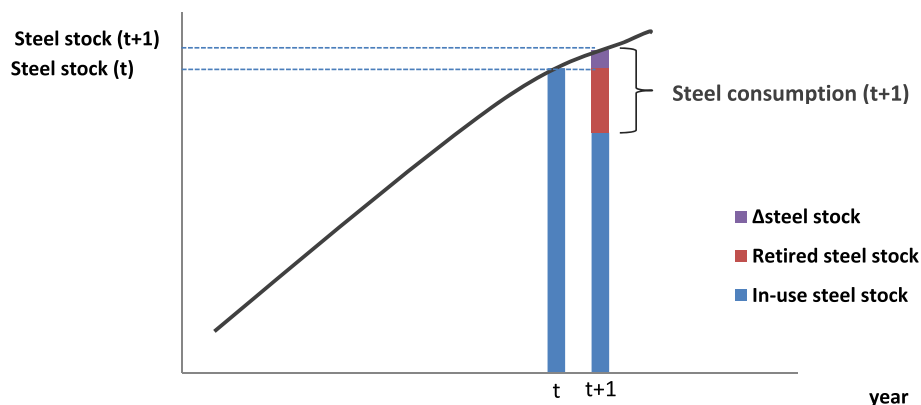


Fig. 4. Steel consumption as a result of steel stock change and retired stock.

- i) “Static Lifetime”: All regions stay in their assigned group for ever (see S3 in the supplementary material);
- ii) “Converging Lifetime”: All regions move to the global average lifetime of the specific sector (the results of the global regression analysis per sector for this scenario are shown in Fig. 3 and Table 3);
- iii) “Long Lifetime”: All regions move to the Long lifetime group;
- iv) “Medium Lifetime”: All regions move to the Medium lifetime group;
- v) “Short Lifetime”: All regions move to the Short lifetime group.

### 3.3. Method for projecting future steel demand

To satisfy the increasing in-use steel stock levels and to replace the steel stock that reached the end of its lifetime and will be retired, “new” steel will need to be added each year (see Fig. 4).

The future annual steel consumption can thereby be calculated by adding the difference in steel stock levels ( $\Delta\text{Steel stocks}$ ) between the year  $t$  and the year  $t+1$  plus the amount of steel that is retired in year  $t+1$ , see Eq. (4) [56], and Fig. 4:

$$\text{Annual Steel Consumption}(t+1) = \text{Steel Stock}(t+1) - \text{Steel Stock}(t) + \text{Retired Steel}(t+1) \quad (4)$$

The steel stock in year  $t$  is calculated from Eq. (2) and the retired steel stock from Eq. (3). The steel stock in year  $t-1$  is known.

With this formulation, steel inputs and outputs from building renovations are not considered. Nevertheless, these amounts should be limited as primarily wood, concrete and plastics are used/discarded from repair and maintenance activities in buildings [57].

## 4. Steel projections

This Section presents the results on the steel stock projections, the retired steel stock projections and the steel consumption projections under different scenarios.

### 4.1. Steel stock projections

Fig. 5 shows the estimated future accumulation of total steel stocks in the different regions. Total in-use steel stocks are calculated from Eq. (2) that estimates the future per capita steel stocks multiplied with the future population.

Rest of Asia and Africa have the highest steel stock build-up followed by India. These results show that steel stocks in China will continue only to slightly increase until 2040 to peak at 10.5 Gtonnes (Gt) and will then start decreasing. The peak in steel stocks is estimated to be reached earlier in China than in India. Steel stocks in India are estimated to peak at around 15 Gt in 2070. In Africa steels stocks are projected to start increasing after 2030 and they do not reach their peak point by the end of the century. In the North America and Western Europe, the situation is different as steel stocks are found to only experience slight growth and have basically reached a plateau.

For many regions it is observed that total stock saturation starts at income levels of more than \$20,000 per capita. As the per capita in-use steel stocks saturate at high income levels, any decline seen in Fig. 5 (bottom) is solely attributed to population decline. The income level at which the saturation starts, depends on the shares and developments of the individual sectors. S4 in the supplementary material shows projected steel stocks on a more detailed regional level (26 regions).

Fig. 6 shows when the total per capita stock saturation level ( $S_{sat}$ ) is reached for 26 regions. The regions for which the regression analysis yielded high  $S_{sat}$  levels ( $>10$  tonnes/capita) are the United States, Western Europe, Rest of South Asia, Middle East, Korea, Japan, Canada, and Oceania.

Overall, the total per capita stocks were shown to saturate between 7.2 and 14.2 tonnes per capita. Section S2 in the supplementary material shows the  $S_{sat}$  levels per region and per activity sector as well as the  $a$  and  $b$  parameters.<sup>5</sup> Although per capita steel stock in China (Fig. 6) was experiencing a stronger annual increase in the past years, after 2020 the increase is shown to slow down to saturate at 7.9 tonnes/capita in 2056. This, along with the growing population, explains why total steel stocks are found to increase up to 2040 in China.

As it is assumed that per capita steel stocks remain the same after the saturation level is reached, the only reason total steel stocks decrease after 2040 is due to decreases in population. Results for India are similar, with the only difference that the total per capita steel stock saturates later in time. In India the per capita total steel stocks saturates at 8.7 tonnes.

<sup>5</sup> For a few regions with very low in-use steel stocks (at the beginning of the S-shaped curve) the regression analysis yielded unrealistic results, for example very high  $S_{sat}$ . For these regions, it is assumed that the development would be the same with a similar/close region (see S2 in the supplementary material).

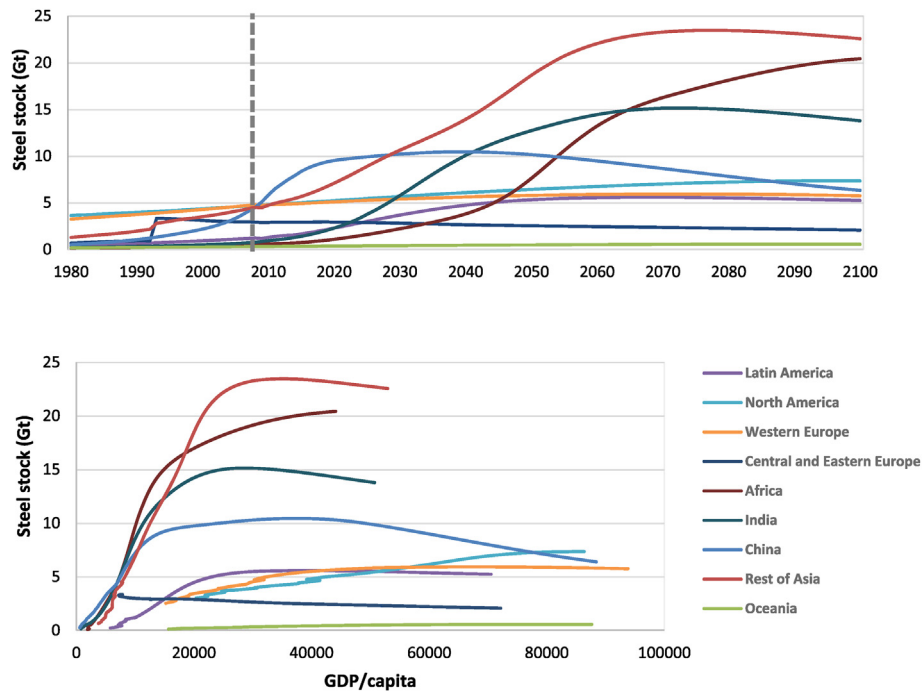


Fig. 5. Total steel stocks in the main world regions (the vertical dotted line distinguishes the projections (right) and the empirical data (left)).

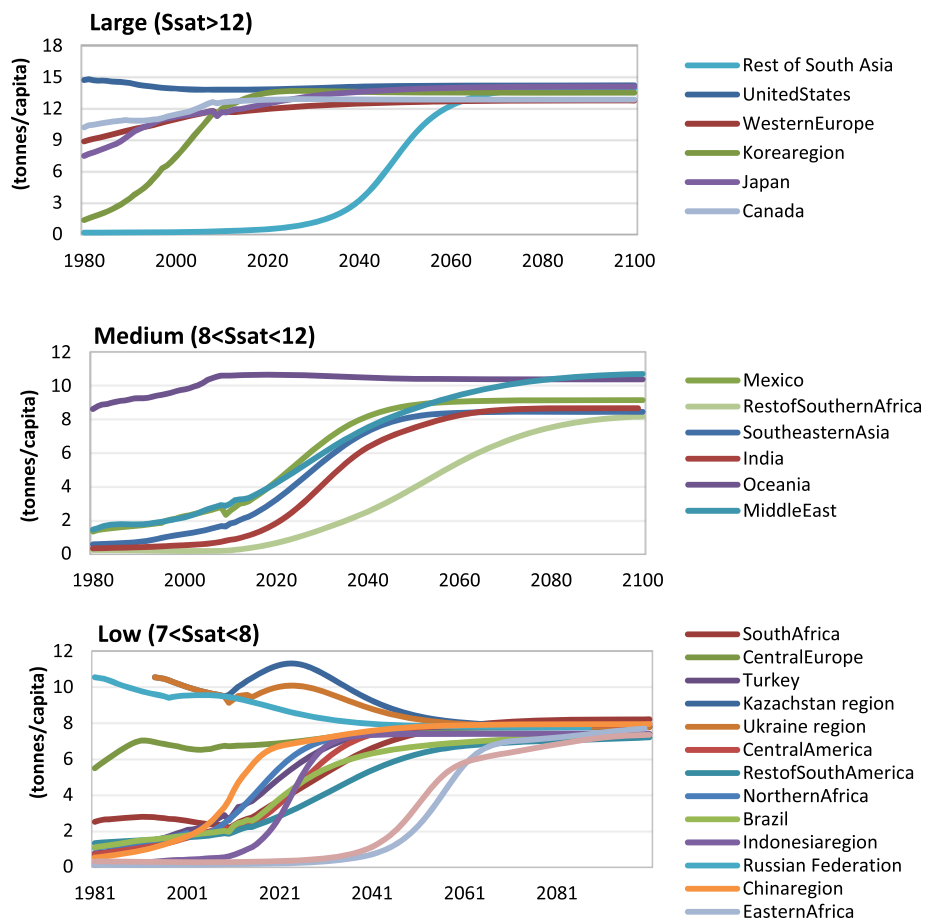


Fig. 6. Total per capita steel stocks (in tonnes/capita); a) regions with large Ssat, b) regions with medium Ssat and c) regions with low Ssat.



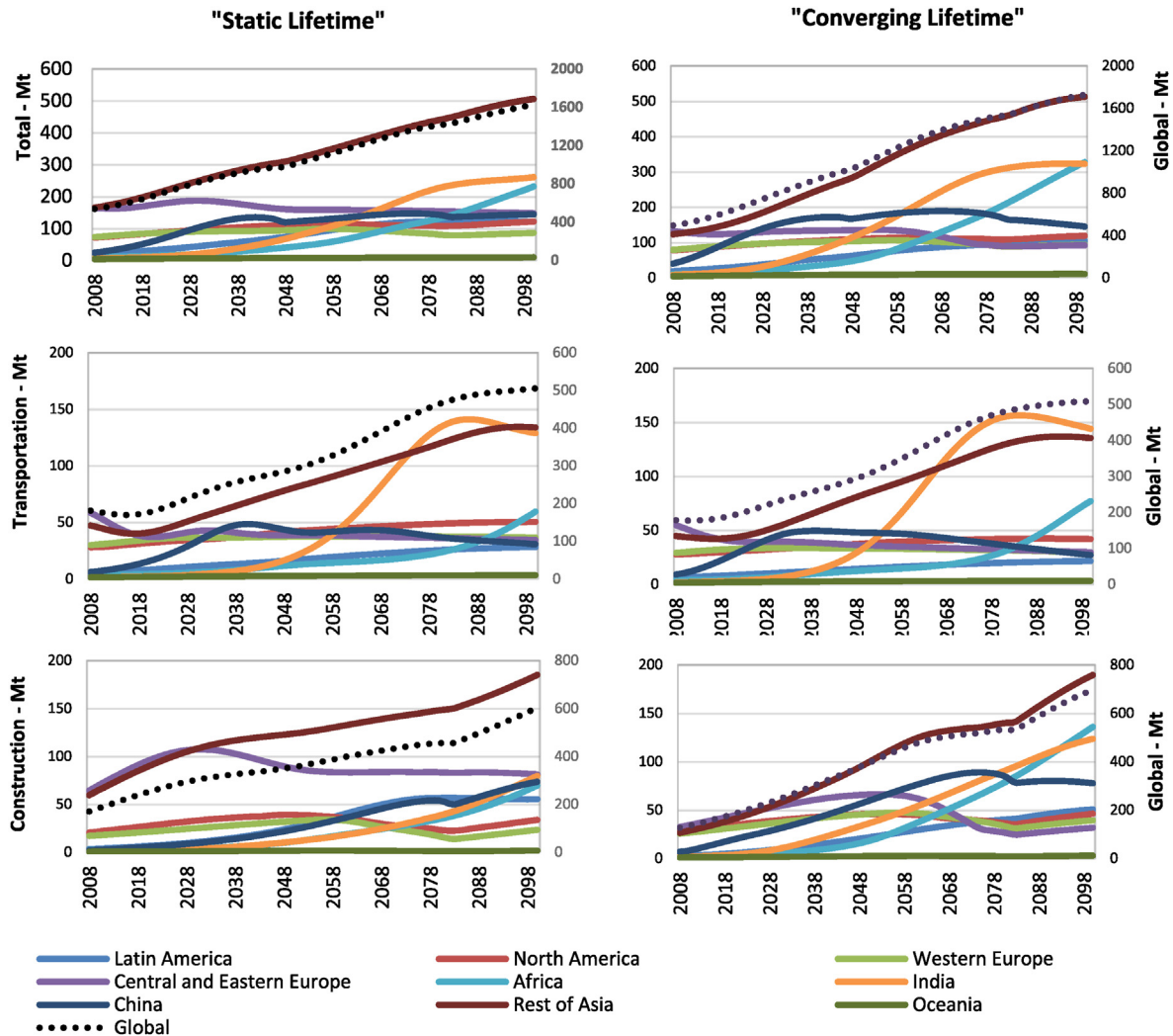


Fig. 7. Total annual volumes of retired steel stocks (in Mt) per region and per activity.

#### 4.2. Retired steel stock projections

Every year, a share of the in-use steel products reaches the end of their lifetime and is decommissioned. Fig. 7 shows the retired steel stocks per activity sector for the two scenarios on lifetime developments i) "Static Lifetime" and ii) "Converging Lifetime".

In the years to come, the volumes of retired steel are estimated to greatly increase from about 500 Mt in 2008 to 1600 Mt and 1700 Mt in 2100 in the "Static" and in the "Converging Lifetime" scenarios, respectively. In 2008 and in the "Static Lifetime" scenario, most of the retired steel came from the transport (180 Mt/yr) and the construction sectors (170 Mt/yr), followed by the machinery (94 Mt/yr) and the others (91 Mt) sectors. In the "Converging Lifetime" scenario the retired steel volumes are very similar, only in the construction sector they appear to be lower (130 Mt/yr).

In the construction sector, where differences are more pronounced, the average lifetime used in the "Converging Lifetime" scenario is 71 years, which is 25 years more than the average lifetime used in the "Static Lifetime" scenario for Central and Eastern Europe, thereby leading to lower retired steel findings. Similarly, for China, India and Africa, the "Converging Lifetime" scenario (71-year average lifetime) finds lower volumes of retired steel than the "Static Lifetime" scenario (100-year average lifetime).

Essentially, large volumes of retired steel in a specific year reveal the years for which consumption was high in the past. For example, in India, steel stock retirement in the transport sector is found to peak between 140 and 160 Mt in 2085. This is because steel consumption in the sector peaked 28 and 20 years prior in the "Static Lifetime" and "Converging Lifetime" scenarios, respectively.

Total steel stocks retired in 2050 or 2100 are estimated to be much higher than in 2008. This will impact the future demand for steel, as to replace the retired steel stock, "new" steel needs to be consumed for the total steel stock to remain on the same level. This dynamic might not be as significant today (low volumes of retired steel and increasing per capita steel stocks), but it can very well be in the future (high volumes of retired steel and saturating per capita steel stocks).

#### 4.3. Steel consumption projections

In the original flow-based approach used in IMAGE and other IAMs, countries/regions with a low income will have a low per capita steel consumption. As the incomes rise, per capita consumption will rise until a certain per capita steel consumption and income level are reached (determined based on analysis of historical trends). At high incomes, and as the economy becomes less material intensive, the steel consumption will decouple from GDP.

In the steel stock-based approach, steel consumption is not linked to GDP/capita but steel stocks are, and they are assumed to saturate when a certain level of GDP is reached (see S5 in the supplementary material).

Fig. 8 shows the global steel stock and steel consumption projections with the use of the stock-based approach (under the “Static Lifetime” and “Converging Lifetime” scenarios) and the flow-based approach (“original”) in IMAGE. The stock-based approach leads to an increasing consumption in the first half of the century, as in the original flow-based approach, but in the second half of the century a decline is forecasted as in many regions stocks will saturate. With the flow-based approach, global steel consumption is estimated to continue its increasing trend in the second half of the century, although it slows down, reaching 2700 Mt/yr in 2100. This is 75% higher compared to the “Converging Lifetime” scenario in the stock-based approach where steel consumption reaches 1500 Mt/yr in 2100.

The steel consumption calculation in the stock-based approach is a two-fold function depending on i) the change in required steel stocks and ii) on the amount of retired steel (see Eq. (4)). When steel stocks saturate (see Fig. 8), the annual demand is only driven by the retired steel, thus leading to a low consumption level through Eq. (4). This obviously also depends on the volumes of retired steel stocks. Fig. 8 shows that before 2050, steel is largely consumed to satisfy the increasing steel stocks, while after 2050 steel is consumed to replace retired steel stocks. This makes steel demand projections very sensitive to the assigned lifetimes, especially for the second half of the century, when large stocks have been accumulated.

To understand the impact the lifetime has on steel projections, it is also shown in Fig. 8 and Fig. 9 the steel consumption under the scenarios “Long Lifetime”, “Medium Lifetime” and “Short Lifetime”. When steel products are used longer (“Long Lifetime”) steel consumption is lower than in the “Converging Lifetime” scenario, reaching 185 Mt/yr in 2100, and when steel products are retired early (“Medium Lifetime”) and very early (“Short Lifetime”), steel consumption is significantly higher, reaching 364 Mt/yr and 536 Mt/yr in 2100, respectively. The difference between the

“Converging Lifetime” and “Medium Lifetime” scenarios can be attributed to the different lifetimes for construction. In “Medium Lifetime” the steel used in construction has a lifetime of 50 years and in “Converging Lifetime” 71 years. Between these two scenarios all other average lifetimes are almost the same (see Table 4).

A drop in steel demand when the stock-based approach is used, is especially pronounced for China, Rest of Asia, India, Africa and Latin America (see Fig. 9). In China, steel consumption is estimated to decrease at an annual rate of 12% between 2013 and 2024 (“Converging Lifetime” scenario) instead of 0.1% with the flow-based approach. In the scenario “Short Lifetime”, steel consumption after 2030 is substantially higher but still a pronounced decrease is found before 2030 as a result of stock saturation.

Steel consumption in India is estimated with the stock-based approach to peak at 505 Mt/yr in 2036 (“Converging Lifetime”), while with the flow-based approach steel consumption climbs to 485 Mt/yr in 2085. India is a country that is projected to not have reached its per capita steel stock saturation point yet. The per capita steel stock logistic growth function results in higher consumption between 2010 and 2040, than in later years. Similar are the cases in China where consumption peaks between 2010 and 2020, and Africa where consumption peaks between 2050 and 2060 and then experiences a very rapid decrease.

Western Europe, a region that has already reached its steel stock saturation point according to the regression analysis, shows a different pattern. Here, annual consumption is estimated to remain constant and is mainly driven by the retirement of steel.

In the scenarios “Medium Lifetime” and “Short Lifetime”, consumption is found to experience a second peak later in China, Africa, India, Rest of Asia. This means that steel consumed at earlier years of strong steel stock growth is being replaced by new steel at the end of its lifetime. However, this is a reflection of the short lifetimes for steel in certain sectors (e.g., 10 years for transport, 38 years for construction).

Overall, global steel consumption between the flow-based and the stock-based approaches shows similar growth in the 2008–2050 period, estimated to reach about 2300 Mt/yr in 2050 (See Fig. 8) increasing at an annual rate of 1.3% and 1.6%,

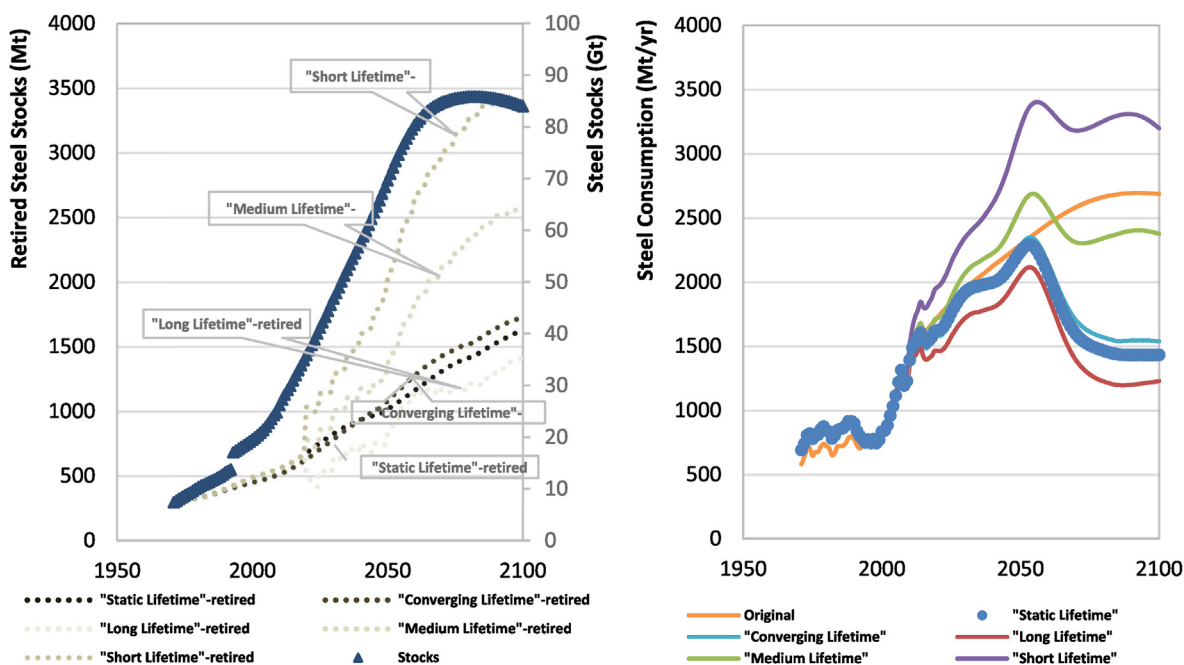


Fig. 8. Global steel stocks, retired steel and steel consumption in IMAGE with the flow-based and stock-based approach.

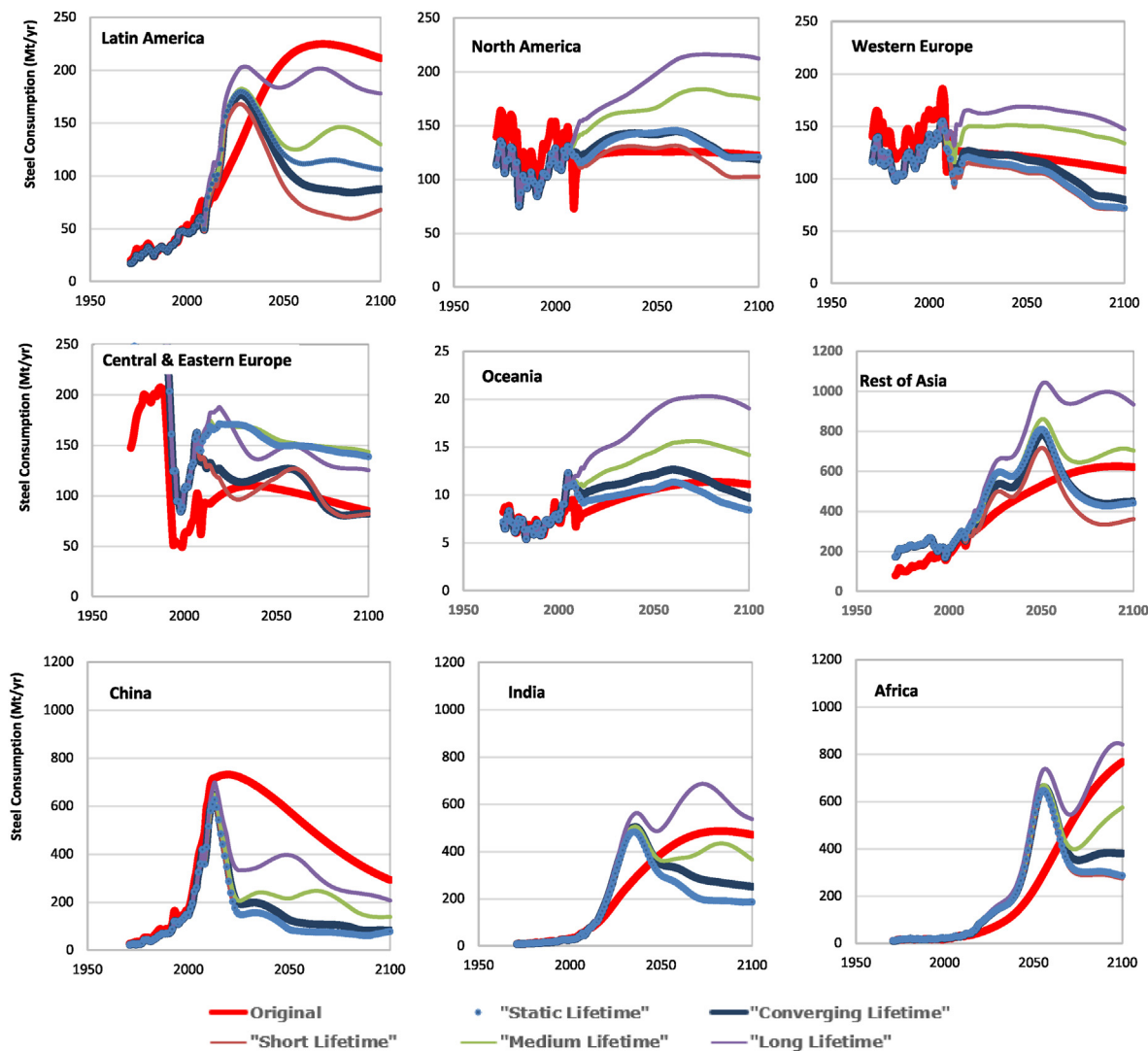


Fig. 9. Regional steel consumption scenarios under different lifetime scenarios.

respectively. Nevertheless, different regions are responsible for this growth [China (25%), Rest of Asia (23%), India (17%) and Africa (10%) with the flow-based, and Rest of Asia (34%), Africa (23%), India (15%) and China (6%) with the stock-based approach]. With the flow-based approach, China is estimated to experience de-growth after 2020. However, the decoupling from GDP is slow in China, while the Rest of Asia catches up. In the stock-based approach ("Converging Lifetime" scenario), demand in China is estimated to drop rapidly. This is because: i) steel stock growth slows down and ii) retired steel is not substantial as existing stocks are not that old (steel stock build-up 2009–2020). In the stock-based approach, after a certain level of stock/capita is reached, absolute steel stocks stop growing unless population grows. Rest of Asia and Africa are estimated to reach peak demand around 2050, which is higher than the demand estimated in the flow-based approach. Projections for Western Europe, North America, Central and Eastern Europe and Oceania provide similar results for both approaches.

In the second half of the century, the projected global steel consumption varies strongly between the two approaches. The flow-based approach sees a continuing increase in demand that reaches a plateau after 2080 (2700 Mt/yr in 2100) while on the other hand, the stock-based approach, sees a decreasing trend

(1500 Mt/yr in 2100). Demand dominating regions are quite similar [Rest of Asia (23%), Africa (29%), India (17%) and China (11%) in the flow-based and Rest of Asia (29%), Africa (25%), India (15%) and China (5%)]. The lower consumption estimates with the stock-based approach are because peak demand is reached earlier in all developing regions while the decrease is more pronounced.

#### 4.3.1. Impact on the energy use forecasts

This study was limited to projecting steel consumption based on a stock-based method for use in IAMs. This section, shows the impact that the method adopted has on energy consumption projections in the IMAGE model.

Scrap availability is an important parameter in energy use projections. The IMAGE model has a scrap model that estimates future scrap availability based on a detailed material flow analysis (MFA) where by future in-use steel stocks are estimated from typical steel product lifetimes and steel statistics (for more information see Ref. [18]). For 2100, IMAGE finds the volumes of steel scrap available for use in steel making at around 1600 Mt/yr. This includes, obsolete, prompt and circulating scrap.

In the stock-based approach, an analysis of the total scrap availability, although crucial for estimating the energy demand

**Table 5**  
Impact of steel demand projection methods on the energy consumption in 2100.

	Stock-based approach	Flow-based approach (IMAGE model)	Stock-based approach (no distinction between EAFs and BF/BOFs)
Apparent crude steel consumption (Mt) <sup>a</sup>	1670	2685	1670
Finished steel consumption (Mt) <sup>b</sup>	1536	2470	1536
Scrap availability (Mt) <sup>c</sup>	1300	1598	—
Steel scrap to production ratio	78%	60%	—
EAF steel production <sup>d</sup>	1182	1453	—
BF/BOF steel production	488	1232	—
Energy consumption in EAFs (PJ) <sup>e</sup>	5083	6248	—
Energy consumption in BF/BOFs (PJ) <sup>e</sup>	8784	22,176	—
Total energy consumption (PJ)	13,867	28,424	30,060 <sup>f</sup>

<sup>a</sup> The stock-based approach calculates the annual consumption of finished steel products while the flow-based approach in IMAGE calculates the annual apparent crude steel consumption. In the stock-based approach, it is assumed that the apparent steel consumption is 8% higher than the computed finished steel consumption. According to Ref. [1], on a global level, the consumption of finished steel products is about 8% lower than the consumption of crude steel.

<sup>b</sup> The stock-based approach computes the finished steel consumption. The finished steel consumption with the flow-based approach is assumed to be 8% lower than the calculated apparent steel consumption.

<sup>c</sup> In the flow-based approach the scrap availability is calculated by a detailed scrap model that considers all scrap sources. In the stock-based approach, it is assumed that 70% of obsolete (end-of-use) scrap is recovered and that 70% of all manufacturing scrap is also recovered.

<sup>d</sup> About 1.1 tonnes of metallics are needed to produce 1 tonne of steel [18].

<sup>e</sup> Assuming that all scrap is used in EAFs and all iron content BOFs comes from pig iron. In reality, significant shares of scrap are used in blast furnaces (3–25%) while about 80% of the metallics used in EAFs is scrap. A significant amount of scrap is also used in cast iron production [18].

<sup>f</sup> For comparison purposes, all steel is assumed to come from virgin ore with the use of BF/BOFs.

which is highly linked to the materials used (scrap vs iron), has not been made as the main scope was to estimate the material demand projections. The scrap availability in this case is thereby estimated by using some key recovery rates (for comparison purposes similar to the ones used in IMAGE). In the “Converging Lifetime”, retired steel (obsolete scrap) is found to reach 1700 Mt/yr in 2100. If 70% of the obsolete scrap is recovered, and another 70% of the scrap generated during manufacturing<sup>6</sup> is also recovered, the scrap available for use in steel making with the stock-based approach is around 1300 Mt/yr.

Assuming an energy use for 2100<sup>7</sup> of 18 GJ/tonne steel for steel manufacturing from iron ore in blast furnaces and basic oxygen furnaces (BF/BOFs), and 4.3 GJ/tonne steel for steel making from scrap with the use of electric arc furnaces (EAFs) [58], the 2100 energy consumption with both approaches<sup>8</sup> can be estimated. Table 5 shows the steel scrap shares in total steel production and the energy consumption with both approaches. Due to the higher steel consumption projections with the flow-based model, the energy use is shown to be 2 times higher when compared to the stock-based approach. This can solely be attributed to the higher steel demand projections found with the flow-based approach.

In a scenario in which the energy required to manufacture steel from iron ore falls to 12.5 GJ/tonne steel,<sup>9</sup> the 2100 energy use with the flow-based approach would be 21.7 EJ and with the stock-based approach 11.2 PJ. The former is still 95% higher as the main energy demand driver is the production and not the energy intensity.

## 5. Discussion of uncertainties

There are multiple uncertainties. Key uncertainties are the assigned stock saturation levels in developing countries that are estimated from past steel stock developments in OECD countries. The estimated overall saturation levels in mature economies cover

a relatively broad range (8–15 tonnes per capita). Insights behind the underlying reasons for differences in saturation levels, could lead towards better approximation of the right saturation level of each developing region. This is especially true for regions where the regression analysis is not able to yield meaningful results. For these regions, the assumption was made that they will follow the same steel stock development as similar regions.

Uncertainties are also inherited from the historical steel stock estimates that are the result of MFA analysis. The MFA analysis is based on limited data with uncertainties related to the activity sector breakdown, and the lifetimes per activity and per country. Other uncertainties that can have a significant impact on the results are the iron content of traded goods, formation of obsolete stocks, and any misreporting of scrap and steel flows.

In the flow-based approach, steel consumption is apparent steel use (ASU) (obtained from the summation of steel production plus imports minus exports) [21]. In the stock-based approach, indirect steel trade is also considered; thus, steel consumption represents true steel use (TSU). ASU is higher than TSU for countries that indirectly export steel (e.g. Korea, China, Germany, Italy) and lower than TSU for countries that indirectly import steel (e.g. Canada, Russia, U.K.). However, when aggregating into regions these differences become smaller. In 2017, global TSU was 6% lower than ASU [59]. In addition, the results when the stock-based approach is used are in finished steel product consumption while in IMAGE in crude steel consumption. On a global level, the steel use of finished steel products is about 8% lower than the crude steel consumption [1].

Steel demand projections, especially for the second half of the century and after the peak on steel stocks, are mainly driven by the retired steel (i.e. stock replacement). Steel consumption is sensitive to the assigned lifetimes of the various steel-containing products. Product lifespans vary among countries and do not remain fixed with time. To add to the complexity, the average lifetime of each steel activity sector and for each region depends on the mix of the different assets, e.g., the share of trucks and ships in overall transportation, which also does not stay fixed with time.

For this reason, the steel consumption is estimated under five scenarios with varying lifetimes. The “Converging Lifetime” and the “Static Lifetime” scenarios are considered to be more representative, both yielding similar regional results with global steel consumption decreasing after 2050. The “Converging Lifetime” scenario assumes that all regions converge to the global average

<sup>6</sup> It is assumed that the scrap recovery rates are at 70%, same as in IMAGE [18].

<sup>7</sup> It is assumed that no innovative processes are implemented, and the energy use is equal to energy use in the Best Practice Technologies (BPTs).

<sup>8</sup> This is just an estimate based on the shares of the scrap availability. Models have many other assumptions/scenarios that can influence the final energy consumption (e.g. the share of the direct reduced iron production process, or the type of casting).

<sup>9</sup> The energy use of producing steel in the DR RES with H2+EAF process is estimated at about 12.5 GJ/tonne [62].



lifetime of the steel activity sector and is very similar to the “Medium Lifetime” scenario (medium retirement rate) except for the construction sector. When the “Converging Lifetime” scenario is used, developing regions with a very long lifetime in transport (group “Long”: 30 years) will move towards a more typical for the developed regions average lifetime (group “Medium”: 20 years). Similarly, regions such as Korea and Japan with very short lifetimes (group “Short”: 10 years) due to the ongoing restructuring and development of strong economic growth, will move to a more typical average lifetime for the sector.

Scenarios “Long Lifetime” and “Short Lifetime” are considered to be extreme. However, they give an indication of steel demand developments when all regions use steel products efficiently (group “Long”) or inefficiently (group “Short”). Here, efficient means no early decommissioning. Scenario “Long Lifetime” in this case could be representative of product lifetime extension in a circular economy. In 2100, steel consumption is estimated to reach 1230 Mt/yr in scenario “Long Lifetime”, and 3200 Mt/yr in scenario “Short Lifetime”, which is not so much more than the current annual consumption. The difference in demand between “Medium Lifetime” and the “Converging Lifetime” scenarios can be attributed to the lifetime used in the construction sector (“Medium”: 50 years, “Converging”: 71 years).

China is a region that, although assigned a long lifetime (group “Long”), literature suggests much shorter lifetimes than the average in the construction sector. Chinese steel demand is estimated at 81 Mt/yr in scenario “Converging Lifetime” and at 140 Mt/yr in scenario “Medium Lifetime”. Scenario “Medium Lifetime” in this case would be more representable for China if it is assumed that reported lifetimes continue for the next 80 years, while scenario “Converging Lifetime” if China would move to a more typical lifetime for the sector.

The analysis focused on the variations of steel projections when different approaches are used. A lower future steel demand in combination with a strong increase of obsolete (end-of-use) scrap availability will result in a much lower energy consumption. However, to thoroughly assess the impact the much-reduced steel demand will have on energy use, certain recovery and processing efficiencies and product quality constraints need to be considered [60]. The current steel recovery rates are not the same for all steel-containing products. About 90% of the decommissioned scrap is recovered in the transportation sector, and while the recovery rates are also high in the construction and the machineries sectors (85% and 90%, respectively), the recovery rates are low for electrical and domestic appliances, 50% [61]. Also, the shares of scrap used in primary steel making will impact the shares of the less energy intensive secondary steel making route on the overall steel production. In addition, the processing efficiencies are less than 100% while they also vary per steel product (e.g. forming losses range from 0.07 for building and infrastructure products to 0.2 in food packaging, and fabrication losses range from 0.06 for infrastructure products to 0.3 in car manufacture and food packaging) and lastly, some iron from virgin ore would have to be produced to dilute the contaminants found in scrap [60].

## 6. Conclusions

The way energy models can profit from the adoption of a stock-based approach is twofold: 1) steel stocks simply serve as a better driver of steel demand and 2) using a stock-based approach has different dynamics (can allow for better modelling of steel scrap availability, enable models to create circular economy scenarios etc.).

Currently, the main drawback is the lack of data. To overcome this, a better understanding of variations on steel stock saturation

levels as well as on the retirement rates on a country level is needed.

The method presented in this paper allows for the simple incorporation of insights on historical steel stock developments and saturation levels gained from detailed MFAs in long-term energy models that commonly use a flow-based approach.

### 6.1. Main conclusions

Based on the stock-based analysis and the comparison of steel consumption projections with the stock-based approach and the flow-based approach, the following main conclusions are drawn:

**The build-up of steel stocks for most developing countries/regions is ongoing and is projected to peak in the coming decades and then gradually decrease.** This is the result of increases in per capita steel stocks driven by higher income levels and population. A slowdown in global steel stock build up is estimated to begin after 2060 and peak by 2080 at 85 Gt. China is projected to peak by 2040, India and Rest of Asia by 2070, and Africa is not projected to peak before 2100. Developed countries/regions have already accumulated the bulk of steel stocks, as per capita steel stocks experience saturation.

**Global steel demand projections with the stock-based and the flow-based approach, are similar in the periods of growth but differ in the periods of decline.** For the first half of the century (year 2008–2050), both approaches show a continuous increase in global steel consumption (albeit with differences between countries). Consumption experiences an annual growth of 1.6% and 1.3% with the stock-based and the flow-based approach, respectively. Only in the second half of the century global steel consumption projections would start to differ for the two approaches. With the stock-based approach, steel consumption will start decreasing after 2050, with an annual rate of 0.8% to reach 1600 Mt/yr by 2100. Small annual changes in total steel stocks that occur when stocks are no longer experiencing high growth (close to saturation) mean that steel consumption is primarily driven by stock retirement. With the currently implemented flow-based approach, steel consumption will continue to grow with an annual rate of 0.3% to reach 2600 Mt by 2100, and lead to about 75% higher annual steel demand compared to the stock-based approach. Given that steel production has a profound contribution to global greenhouse gas emissions, this means that IAMs may currently overestimate the industrial emissions in the last half of the century.

**The volumes of retired steel are projected to substantially increase in the coming decades.** As the high volumes of steel consumed in previous years will reach the end of their lifetimes they will need to be decommissioned. To replace retired steel stock, “new” steel needs to be consumed for the total steel services provided in an economy to remain on the same level. It is found that about 1700 Mt/yr of obsolete scrap will become available in 2100, equal to the steel demand in the same year (retired steel is the only driver of steel demand after stocks have saturated). This could mean that future steel demand could be to a great extent satisfied by reusing obsolete scrap produced with the low energy intensive secondary steel making route.

**The projected regions to dominate in global steel consumption vary between the stock- and the flow-based approach.** With the flow-based approach, in 2050 China will be the main steel consumer (25%), followed by Rest of Asia (23%), India (17%) and Africa (10%). With the stock-based approach Rest of Asia will dominate steel consumption (34%), followed by Africa (23%), India (15%) and China (6%) (“Converging Lifetime” scenario). Chinese demand decreases drastically as steel stocks saturate early and accumulated steel stocks are not mature enough to be decommissioned. In 2100, dominating regions are quite similar [Rest of



Asia (23%), Africa (29%), India (17%) and China (11%) in the flow-based and Rest of Asia (29%), Africa (25%), India (15%) and China (5%)] with both approaches.

**Following the stock-based approach, the model projects steel consumption in China and India, to peak at 625 and 484 Mt/yr, respectively and then decrease drastically.** With the stock-based approach steel consumption was projected to abruptly decrease at an annual rate of 12% in China and 3.3% in India within a 10-year period after the peak has been reached. This shows that decreasing GHG emissions may be hard when many developing regions are still building-up their stocks, but it may be easier later when stocks have saturated. For Western Europe and North America, future steel consumption was shown to remain constant. When the flow-based approach is used, steel consumption in developed economies is quite stable.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Credit author statement

**Katerina Kermeli:** Conceptualization, Methodology, Software, Writing-Original & draft preparation; **Oreane Edelenbosch:** Conceptualization, Methodology, Software, Reviewing and Editing Original & draft preparation; **Wina Crijns-Graus:** Supervision, Reviewing and Editing; **Bas J. van Ruijven:** Supervision, Reviewing Original manuscript; **Detlef P. van Vuuren:** Conceptualization, Reviewing and Editing Original & draft; **Ernst Worrell:** Supervision, Reviewing Original manuscript.

### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.energy.2021.122434>.

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