# Worldwide resource efficient steel production

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## Abstract
Steel production processes are energy and emission intensive, but there are variations due to different choices of production routes, product mixes and processes. This study analyses future steel production globally, with focus on the rising availability of steel scrap, and implications for steel production capacity planning. We evaluate the development of steel demand, using the Steel Optimization Model, which provides a region-detailed representation of technologies, energy and material flows and trade activities. We link it to the Scrap Availability Assessment Model, which estimates the theoretical steel scrap availability. The modelling horizon stretches until 2100, with 2050 serving as a benchmark for the analysis. The scenarios require a range of inputs to estimate regional pathways for steel demand including demographic development and economic growth, and these affect scrap availability. The results show that aggregated crude steel production will evolve into an almost balanced split between the primary production route using iron ore and secondary production from steel scrap by 2050 and the share of EAF will exceed by 2060 the production in BOF globally. The results also show a global increase in scrap use from 611 Mtonnes in 2015 to 1.5 Gtonnes in 2050, with highest growth being for post-consumer scrap. In 2050, almost 50 % of post-consumer scrap is expected to be traded, with the main exporter being China and major importing regions being Africa, India and other developing Asian countries. Surprisingly, the increase in scrap use does not depend much on the introduction of a global carbon price until 2050. The results are important for producers contemplating new investments, since regional availability, quality and trade patterns of scrap will influence production route choices, possibly in favor of secondary routes. Also policy instruments such as carbon taxation may affect investment choices, and favor more energy efficient and less carbon-intensive emerging technologies.

## Introduction
Iron and steel production processes are energy intensive and responsible for significant amounts of greenhouse gas emissions. From 2002 to 2012, the volume of steel production has increased 72 % globally, and emissions have increased by 75 %, representing approximately 25 % of the global industrial emissions (Serrenho et al., 2016). There are, however, large variations in emissions depending on the production route, product portfolios and carbon intensity of the fuel mix. Many efforts are being made to reduce energy intensity and emissions in the sector. In fact, these efforts have resulted in a 50 % decrease in specific energy consumption in iron and steel production in the last 30 years (World Steel Association, 2012a).

Increasing steel-scrap recycling has contributed to reduced emissions, particularly because the route using recycled steel (*secondary production route*) requires 56 % less energy than the route using iron ore in the primary steel production (Institute of Scrap Recycling Industries, 2012). More specifically, the production of one tonne of secondary steel requires 9–12.5 GJ/tonne, while 28–31 GJ/tonne are required through the BOF (primary) route (Yellishetty et al., 2011). Scrap recycling is facilitated by the physical properties of steel as a material, since it can be almost indefinitely recycled without losing its properties

(EUROFER, 2016). Secondary steel production using Electric Arc Furnace (EAF) has economic and environmental advantages in comparison to the *primary steel production route* using Blast Oxygen Furnaces (BOFs hereafter), implying lower energy costs and fewer steps along the process chain (Söderholm and Ejdemo, 2008).

The primary production route can be used for producing both long and flat steel products. Usually, this route is chosen to produce High Quality (HQ) steel flat products, as it requires virgin material (iron ore). The share of scrap used in this case is usually supplied at plant level, the so-called pre-consumer scrap (high-quality scrap – HQ scrap hereafter). The secondary route (or Electric Arc Furnace – EAF hereafter) is mostly used for long products, for which HQ of scrap is not required, and thus post-consumer scrap (low-quality scrap – LQ scrap hereafter) can be used. EAF is also used for the production of special steels (incl. stainless), and there are many EAFs in North America producing flat carbon steel.

Several studies have previously investigated material flows, steel stocks and the role of scrap in steel production. Some of them focus on specific countries or regions (Kuramochi, 2015; Serrenho et al., 2016; Wang et al., 2015, 2014; Wubbeke and Heroth, 2014; Xuan and Yue, 2016), while others have a multi-region or global perspective (Morfeldt et al., 2012; Oda et al., 2013; Pauliuk et al., 2013a, 2013b; Yellishetty et al., 2011). Other studies focus on investigating current and potential recycling rates that can be achieved to close the production cycle (Graedel et al., 2011; Wang et al., 2007a). This study builds upon knowledge gained from previous studies, but links detailed scrap availability modelling at regional level with integrated modelling for steel production. In addition, the opportunities that new emerging technologies offer to reduce energy use and emissions are explored, as well as the impact of new policy schemes. The results of the study are useful in the discussion of how new steel production routes and material recycling can contribute further to the concept of circular economy at regional and global level.

In this paper, future steel production is analyzed at a global scale, with focus on the rising availability of steel scrap, and implications for production capacity planning. A reliable estimation of steel demand in different regions, together with an evaluation of scrap availability can provide valuable information to support (i) capacity planning of iron and steel, and (ii) investment choices in primary or secondary steel production. An increased share of secondary routes in future steel production could play a significant role in the decarbonisation of the sector, as well as in the reduction of energy demand and total production costs. This study's novelty in comparison to previous literature can be summarized in the following key aspects undertaken: (i) linking the Scrap Availability Model and Steel Production Model by iterative process; (ii) differentiating steel scrap in different quality categories (own, HQ and LQ scrap) and; (iii) linking the aforementioned scrap categories to steel production routes.

As new investments are contemplated, it is important to understand how the balance of steel demand and production will evolve regionally and globally and which production routes and technologies will be most attractive. Regional availability of scrap, quality and trade patterns will influence investments and favour one route over the other. In addition, policy instruments such as carbon taxation may affect investment choices, and potentially favor emerging technologies that reduce the energy and emissions intensity of steel production. In this context, we aim to answer the following research questions:

- How will scrap availability and quality affect investments for steel production regionally?
- How will the balance of steel demand and production develop in different world regions? What investments can be anticipated in the world regions, either in form of retrofitting existing installations or in green field projects?
- What is the role of climate policy instruments and emerging technologies in future technology choices?

Following the present introduction, the next section of the paper presents the methodologies and modelling approaches, as well as the scenarios used for the analysis. After that, the modelling results are discussed and, finally, the main conclusions from the study are highlighted in the concluding section.

## Methods and modelling scenarios

To evaluate the development of steel demand in the world, we use a TIMES model-based Steel Optimization Model, which provides a detailed representation of technologies, energy and material flows and trade activities in 13 different regions. We link it to the Scrap Availability Assessment Model (SAAM) which estimates the theoretical steel scrap available at regional level. The modelling horizon stretches until the year 2100, with 2050 serving as benchmark for the analysis. The list of regions taken into account for the analysis can be found in the Appendix.

The scenarios covered in this study require a range of inputs to estimate regional pathways for steel demand, which result from demographic development and economic growth, and affect scrap availability. The structural equation for steel demand modeling has been inspired by the error-correction mechanism (Engle and Granger, 1987). In this formulation, short and long run reactions are considered. In the short period, demand fluctuates with GDP. The second term in the specification is the so-called error–correction term, stating that the more demands deviates from some theoretical pathway, the higher the correction towards that. This theoretical pathway is derived from a per capita steel-stock stabilization assumption. Per capita steel-stock follows an S shaped stabilization curve, stabilizing at levels between 12 and 14 ton steel per capita for developed countries (Pauliuk et al., 2013b). Over a long period the steel-stock per capita income is considered as being related to income per capita and is being projected and steel demand (ASU) is derived from the steel-stock.

The scenarios considered include: (i) *variations in $CO_2$ price, either unilaterally in Europe or globally*, and (ii) *variations in steel recycling rates, both for post-consumer scrap (LQ scrap) and for pre-consumer scrap (HQ scrap).* Using different scenarios and sensitivity analysis, we identify the most important sources of uncertainty.

A key input in the analysis is the estimation of future steel demand. One of the methods defined by the World Steel Association for measuring steel demand is the Apparent Steel Use (ASU). The ASU is defined as "deliveries minus net exports of steel industry goods" and increases the accuracy of steel demand estimations by incorporating the trading aspect (World Steel Association, 2012b).

### TIMES-BASED STEEL OPTIMIZATION MODEL

The Steel Optimization Model was developed by VITO (Flemish Institute for Technological Research) and is based on the TIMES modelling framework (Loulou and Labriet, 2008). It represents the world energy system in 13 regions (see Appendix for a list of regions). TIMES uses a bottom-up modelling approach, using explicit representation of technologies, energy and material flows and trade flows. Different production chains for steel production are represented. All technologies are characterized by specific input and output requirements. Besides technical parameters, economic parameters such as CAPEX (capital expenditure) and OPEX (operating expenditure) are relevant input variables for the model. TIMES can be described as a linear programming simulation tool, which selects the investment options that best fulfil the demand scenario with the lowest costs. In other words, TIMES optimizes the total discounted costs (CAPEX, OPEX, fuel and material and transport costs) over the modelling time horizon. In the Steel Optimization Model, the following (simplified) possibilities for steel production are defined: (i) the Blast Oxygen Furnace (BOF) route; and (ii) the Electric Arc Furnace (EAF) route. Both routes are capable of producing flat steel and long steel products.

The available technologies within the model can be separated into existing production installations (*residual capacity*), *new installations* which need to be constructed before they can be used (*green field investment*), and *emerging technologies*, which do not currently exist in the market but are considered as market-ready at some point in time during the model horizon. Three emerging technologies, which are currently not established in steel production, are considered as market ready by 2020: (i) *top gas recycling* in the blast furnace; (ii) *JET BOF* technology; and (iii) a *scrap purification* technology.

With the *top-gas recycling* technology, the required amount of coke, coal and electricity is reduced compared to the common BOF technology. The technology is assumed to be made available for the market in the year 2020. Based on expert interviews, the parameters established for the model are shown in Table 1.

The *JET BOF* technology offers the possibility to increase the share of scrap in the basic oxygen furnace. The technology consists of equipment that blows oxygen, lime and coal from the bottom into the converter and a hot blast lance which blows oxygen and 1,300 °C hot blast into the bath from the top. For the purpose of our model, we assume a steel scrap share of 18 % for the traditional BOF converter, and up to 50 % for the BOF with JET technology. In the model, this technology is available for investments from 2020 onwards.

The last emerging technology is a *steel scrap purification* process. The basic assumption is that impurities within the steel scrap can be removed at a certain cost, and thus it becomes possible to convert LQ scrap to HQ scrap. As there is no available literature for the cost of such a process, two variants have been assumed. In the standard variant, the cost for purification is relatively high and exceeds international transport costs. This means that exporting LQ scrap is cheaper than scrap purification. In the low variant, scrap purification is cheaper than international transport cost (see Table 2).

For the two defined steel production routes, the most recent available crude steel production data from the World Steel Association (WSA) were used to establish production capacities for each existing technology in the 13 world regions. Installed capacity has been estimated from historical production figures. The base year used is 2013 for all modelling scenarios. Available data regarding the remaining lifetime of existing installations was also fed into the model. If remaining lifetime data was not available then historic production data from the WSA were used to calculate an approximation of residual capacity in each region, based on the assumption of 85 % availability factor and 40 years lifetime for each installation. The residual capacity capital expenditure is considered sunk costs, meaning these costs are not accounted for in the cost minimization equation of the model. As a result of this exercise, the different regions of

**Table 1. Comparison of input/output commodities for BOF and BOF with top gas recycling.**

| Commodity | BOF | BOF with Top Gas Recycling (BOF TGR) | Comparison BOF vs. BOF TGR |
|---|---|---|---|
| Coke gas input | 9.3 GJ/tonne | 5.9 GJ/tonne | -37 % |
| Coal input | 6.2 GJ/tonne | 5.2 GJ/tonne | -16 % |
| Electricity input | 0.5 GJ/tonne | 0.2 GJ/tonne | -60 % |
| Blast furnace gas output | 3.25 GJ/tonne | 0.7 GJ/tonne | -78 % |

*Source: Parameters derived from consultation with steel production technology experts.*
*Note: Only commodities listed, with variation in input or output per pig iron output (in Mtonne).*

**Table 2. Technical parameters of emerging steel scrap purification technology.**

| | Standard variant | Low cost variant |
|---|---|---|
| CAPEX | €200/tonne | €100/tonne |
| VAROM (Variable Operation & Maintenance Cost) | €30/tonne | €15/tonne |
| FIXOM (Fixed Operation & Maintenance Cost) | €10/tonne | €5/tonne |
| Efficiency | 90 % | 90 % |
| Lifetime | 40 years | 40 years |

*Source: Consultation with steel production technology experts.*

**Table 3. CAPEX and retrofit fraction for technology investments.**

| Technology | CAPEX | Unit | Retrofit fraction |
|---|---|---|---|
| Finishing long | 85 | €/tonne-year | 0.5 |
| Finishing flat | 185 | €/tonne-year | 0.5 |
| Casting | 80 | €/tonne-year | 0.5 |
| BOF | 113 | €/tonne-year | 0.5 |
| EAF | 169 | €/tonne-year | 0.5 |
| Blast Furnace | 273 | €/tonne-year | 0.5 |
| Sinter | 56 | €/tonne-year | 0.3 |
| Cokes plant | 399 | €/kW | 0.3 |
| DRI | 230 | €/tonne-year | 0.5 |
| Pellets (DRI) | 62 | €/tonne-year | 0.3 |
| Blast furnace gas for electricity plant (ELE) | 1,200 | €/kW | 1.0 |
| Coal ELE | 1,800 | €/kW | 1.0 |
| STEG gas ELE | 960 | €/kW | 1.0 |
| Clinker production | 270 | €/tonne-year | 1.0 |

*Source: Consultation with steel production technology experts.*

the world have very different profiles in terms of residual production capacity. The more recent investments (as for example in the case of China), imply later depreciation of the residual capacity within the region.

For investments in future production capacities, technology parameters with increasing efficiencies are developed along the time line of the modelling horizon. When new production capacities are required, two choices are available according to the model. CAPEX can be spent to retrofit existing installations or be invested in greenfield projects, including energy efficiency improvements. Retrofitting existing plants requires less capital and is limited as steel production decreases. Based on expert interviews and the study "Steel's Contribution to a Low-Carbon Europe 2050" (The Bostonne Consulting Group & Steel Institute VDEh, 2013), CAPEX and retrofit parameters were developed, as listed in Table 3 and fed into the model.

In summary, at some point in time in the modelling horizon, a region has an overall production capacity that is an aggregate of residual capacity of what was already established in the base year, some retrofit capacity of ting installations, and new production plants built in the form of greenfield investments where needed. The detailed scrap availability values extracted from the Scrap Availability Assessment Model (SAAM) are fed into the Steel Optimization Tool, improving the accuracy of results and their relevance for the steel sector.

### SCRAP AVAILABILITY ASSESSMENT MODEL (SAAM)

The Scrap Availability Assessment Model (SAAM) was developed in the Energy and Climate Studies Unit at KTH as part of the KIC InnoEnergy-funded project ESA2 (Energy Systems Analysis Agency). The model calculates the theoretical maximum scrap availability at a specific point in time, for a specific country or region. The total scrap becoming available is divided into scrap that is actually recycled and scrap that remains unexploited. SAAM provides information on the availability of steel scrap and the accumulated steel stock in society, thus filling a gap in the comprehensive mapping of changes in steel stock for the countries included in the World Steel Association database. Steel scrap availability is influenced retrospectively by the steel products' life cycle. For this reason, we collected historical data for the ASU before proceeding to estimations for scrap availability in the future. Another input needed is the future steel demand projections, and this is where the linkage between the SAAM and the TIMES-based model is created in a recursive manner.

The methodology for development and application of SAAM is described in more detail in (Morfeldt et al., 2015) and (Xylia et al., 2014). SAAM was updated from a first global version in the first study, to a second version in which country-detail and regional aggregation was included. For the present study, SAAM is updated further to include steel scrap trade, and further refined in relation to recycling rates and product lifetime assumptions. The steel stock and scrap availability calculations are also updated with the use of smoothing functions that increase accuracy of the results. The historical data on ASU for finished steel products for 109 countries was gathered from 1967 to 2013 from the World Steel Association (2013). Since no data were available for the period before 1967, an annual growth of 3.5 % was assumed for the previous years, in line with assumptions made by Grosse ( 2010).

SAAM calculates the scrap availability for each country, using specific country data for the sector split into the various steel products and their lifetimes (see (Pauliuk et al., 2013b). The model divides available scrap into three categories: (i) *own scrap* (produced within the steel plant from production processes); (ii) *new scrap* (also known as pre-consumer, or HQ scrap, produced from steel manufacturing processes); and (iii) *old scrap* (also known as post-consumer, LQ scrap, produced at the end-of-life of steel products) (Morfeldt et al., 2015). Own and new scrap are considered to be immediately available for recycling. Old scrap becomes available after some time, depending on the lifetime of each steel product category (e.g. appliances, vehicles, construction, and machinery). Own scrap is estimated by SAAM, but it should be noted that this is reported separately from pre-consumer HQ scrap in this study, where needed. SAAM uses a bottom-up approach that combines historical steel consumption figures for different categories and assumptions on recycling rates based on available literature (see Graedel et al., 2011; Pauliuk et al., 2013b; Wang et al., 2007b, among others).

#### SCENARIO DEFINITION

In this study, different scenarios at two levels were considered. At first level, a variation in steel recycling rates, both for aggregated scrap recycling (HQ and LQ scrap) and with variation solely in pre-consumer (HQ) scrap is assumed. At second level, a variation in $CO_2$ price, either unilaterally in Europe or globally, is assumed and applied in the modelling process with the Steel Optimization Tool.

When defining the scenarios for recycling rates, the aim was to cover the most important sources of uncertainty, such as potential recycling of LQ scrap and availability of pre-consumer (HQ) scrap. We assume slower recycling rate growth in Scenario 1, achieving 80 % by 2050 at average global level and aggregated for all product categories. In Scenario 2, the increase in the recycling rate is faster and higher, reaching 85 % by 2030 at average global level and aggregated for all product categories. Both scenarios are in line with assumptions for current recycling rates and projected maximum global recycling rates available in the literature (see Graedel et al., 2011; Morfeldt et al., 2012). Scenario 3 focuses on the pre-consumer scrap production rates. Technologies for steel production and steel product manufacturing in general are constantly improving. Therefore, the amount of pre-consumer scrap from such processes is expected to decrease, thus potentially causing a deficit in readily available, HQ scrap. The three scenarios regarding scrap availability are presented in Table 4.

For the Steel Production Optimization Model, the following scenarios were defined:

i. A baseline scenario in which no $CO_2$ tax is applied.

ii. A second scenario with a $CO_2$ cost of €10 in 2015 and €15 from 2020 onwards per tonne of emitted $CO_2$. Within this scenario, two variations are considered: one in which there is only an emissions trading scheme (ETS) for Europe, called "*T15EU*", and one in which such costs are imposed globally called "*T15WO*".

iii. The third scenario consists of two variations: an emissions trading scheme starting at a price level of €10 for 2015, but consider a gradual increase to €50 by 2050, for Europe only ("*T50EU*") or the world ("*T50WO*"). An overview of the scenarios is provided in Table 5.

Scrap purification technologies are also taken into account in these scenarios, and the costs for such technologies are included in the scenarios for the EU region. Scenarios with the lower cost for purification have an indication with "*pur*". For example, T15EUpur is identical to T15EU except for the lower cost for the scrap purification.

## Results and discussion

#### REGIONAL STEEL DEMAND PROJECTIONS

The apparent steel use (ASU) projections are illustrated in Figure 1. A sharp slowdown is expected for China from 2020 onwards. This decrease is explained by the saturation effect of the per capita steel stock and the demographic evolution in China, and results from the one child policy to date. Around 2055, one can observe a second turning point in the ASU projection for China. This one is related to the age structure of the steel stock. The steel stock that is accumulated between 2000 and 2020 comes to the end of its life and has to be replaced. Similar patterns are observed in other regions. Around 2050–2055, the world steel market will be dominated by four regions; China, India, ODA and Africa, having almost equal shares.

These projections entail some level of uncertainty, which is affected by parameters such as the assumption of steel stock per capita stabilization at 12 tonnes/capita (see Pauliuk et al., 2013b); the population development (here the medium fertility scenario of the UN is used (United Nations, 2015a); assumptions for the labor productivity growth; and the lifetime assumption for steel products.

#### SCRAP AVAILABILITY – RESULTS FROM SAAM

The basis for calculating scrap availability is the Apparent Steel Use (ASU). Figure 2 shows the historical scrap availability estimations from SAAM from 1970 to 2013, as well as the future scrap availability estimations until 2100 based on the three scenarios previously defined.

Scenario 3 shows slightly lower scrap availability due to the lower amount of HQ scrap available in comparison to the other two scenarios. This analysis indicates that the sensitivity of total scrap availability (and consequent scrap use in steel production) is low for the different recycling rates assumed in the re-

**Table 4. Steel scrap availability scenario definitions.**

| | LQ scrap recycling rates | HQ scrap shares | HQ scrap recycling |
|---|---|---|---|
| Scenario 1 (lower LQ scrap) | 60 % (2013) to 80 % in 2050 | stable | 100 % |
| Scenario 2 (baseline) | 60 % (2013) to 85 % in 2030 | stable | 100 % |
| Scenario 3 (lower HQ scrap) | 60 % (2013) to 85 % in 2030 | 25 % lower by 2030 | 100 % |

**Table 5. Steel Optimization Model Scenario Definitions and $CO_2$ costs.**

| | EU 30 | Rest of the World | EU 30 | Rest of the World |
|---|---|---|---|---|
| Baseline | €0 | €0 | €0 | €0 |
| T15EU | €10 | €0 | €15 from 2020 | €0 |
| T15WO | €10 | €10 | €15 from 2020 | €15 from 2020 |
| T50EU | €10 | €0 | up to €50 in 2050 | €0 |
| T50WO | €10 | €10 | up to €50 in 2050 | up to €50 in 2050 |

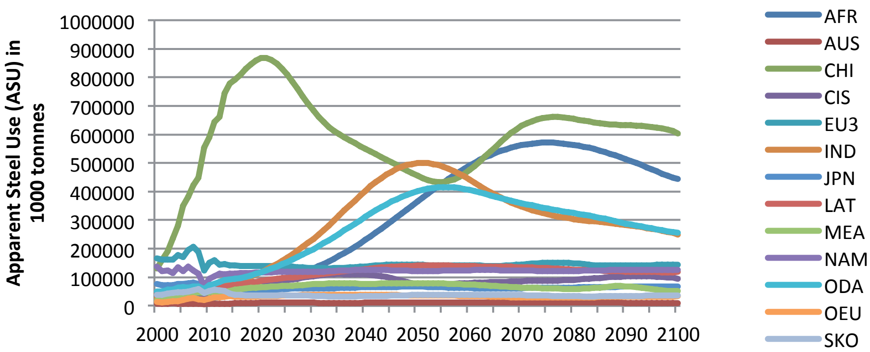


*Figure 1. Apparent Steel Use projections.*

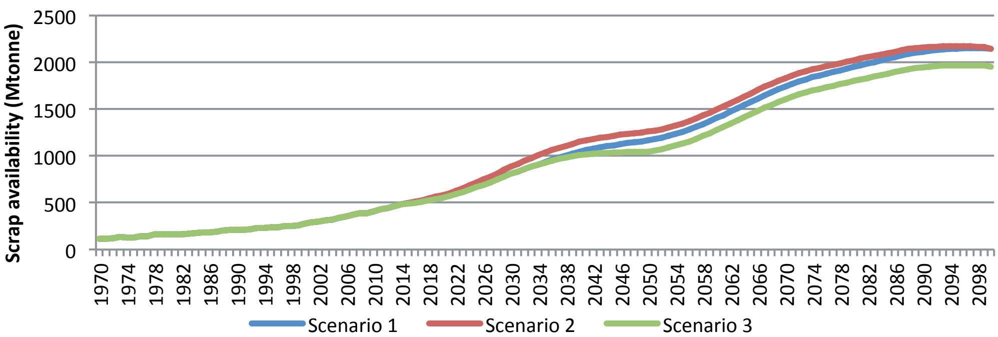


*Figure 2. Scrap Availability (Mtonne) 1970–2100.*

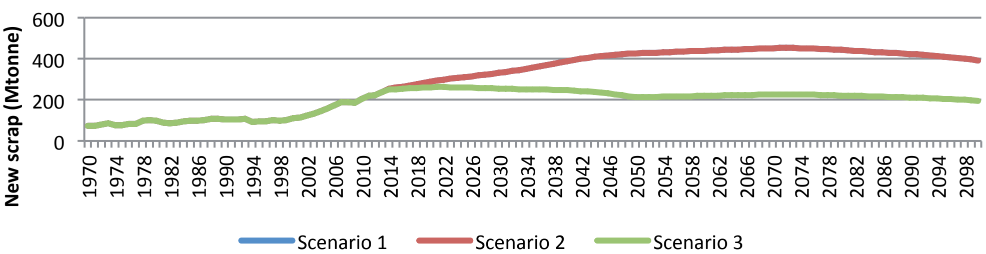


*Figure 3. Pre-consumer Scrap (New or HQ) Scrap) (Mtonne) 1970–2100.*

spective scenarios. Therefore, in the results presented hereafter in this paper, the focus is on Scenario 2 (the baseline scenario for scrap availability).It should be noted that uncertainties related to the estimation of steel demand also have impact on the scrap availability estimations since the two parameters are linked, as previously explained.

Figure 3 shows the pre-consumer scrap availability, which quadruples by 2050 compared to 2013, from 200 Mtonnes to between 731 (Scenario 1) and 831 (Scenario 2 and 3) Mtonnes. Figure 3 also shows the sharp decrease of new (HQ) scrap availability when steel production efficiency improves so as to reduce new scrap. This estimation for LQ scrap availability is in line with previous estimations that showed a global LQ scrap availability of ca. 760 Mtonnes by 2050 (Oda et al., 2013). Figure 4 shows a sharp increase of available LQ scrap after 2020.

Looking into post-consumer scrap availability per region, Figure 5 shows indicatively the results of Scenario 2. Here China experiences a rapid increase of LQ scrap availability by 2020, reaching a first peak by 2050. The EU region is leading in LQ scrap availability before China takes over but, as the steel stock from China, Africa, India and ODA gradually increases due to faster development, the amount of available LQ scrap also increases. Therefore, EU available LQ scrap will be of less importance after 2020, compared to the aforementioned regions. Previous studies have estimated LQ scrap availability in China to reach ca. 400 Mtonnes by 2050 (Wang et al., 2014; Xuan and Yue, 2016). Our projections are within the same range, albeit somewhat lower at ca. 350 Mtonnes.

It should be pointed out that SAAM calculates the *theoretical amount of scrap becoming available in a year*, based on global estimations of recycling rates from literature and national product categories split, as explained previously. It is therefore not guaranteed that all scrap becoming available under these theoretical conditions will actually be recycled, but it is safe to assume that in most cases it will be so, as scrap is a valuable commodity. The validation of the model, based on historical values from the Bureau of International Recycling (BIR), show that SAAM calculates global scrap availability values that are quite close to the historical values. According to BIR (Bureau of International Recycling, 2012), the amount of scrap that was actually recycled in 2013 was 245 Mtonnes. SAAM calculates the post-consumer scrap availability in 2013 to be 225 Mtonnes, which is a difference of 8 %. If one adds scrap that has perhaps been traded and not recorded properly in international trade databases such as COMTRADE (United Nations, 2015b), or scrap used by foundries not being taken into account, then SAAM's results are very close to reality when it comes to estimations at global level.

At regional level, there are more uncertainties when calculating scrap availability, due to the insufficient trade information and the existence of *indirect steel trade* (embedded steel in products produced in one region and sold to other regions) (World Steel Association, 2012b). Such is the case for of China for example, where SAAM calculates higher scrap availability by on average 30 % more compared to actual BIR values for 2010–2013. On the other hand, SAAM calculates 50 % less scrap availability compared to the actual scrap recycled in the EU according to BIR in the period from 2010 to 2013. This clearly illustrates the problem with indirect steel trade, as apparently a high Chinese ASU leads to large amount of products sold to the high-income EU region, which then utilizes the scrap at the end of the product lifetime. Including indirect steel trade in SAAM would be highly beneficial for increased result accuracy at regional level, and this can be done in the future. The problem when accounting ASU and the impact of indirect steel trade are also confirmed for the case of UK, as per documented in Serrenho et al. (2016).

#### WORLD STEEL PRODUCTION – RESULTS FROM STEEL OPTIMIZATION MODEL

Figure 6 shows a steady increase in global steel production, reaching approximately 2.7 Gtonnes of combined long and flat steel production in 2050, and peaking around the year 2070 at approximately 2.8 Gtonnes. The split between global EAF production and BOF production will evolve from a 1:2.5 relation in 2015 (1.16 Gtonnes via BOF versus 0.46 Gtonnes via EAF) towards an almost balanced production split in 2050 (ca. 1.5 Gtonnes via BOF versus 1.2 Gtonnes via EAF). In 2060, the share in EAF will exceed the production in BOF globally.

Analyzing the global flat and long steel production separately, we found that demand for both product groups will steadily increase and experience a peak production of 1.6 Gtonnes for flat products and 1.2 Gtonnes for long products in 2070. The evolution of the production routes for both product groups will be different. While the EAF share increases from 38 % in 2015 to 70 % in 2050 for long steel, the flat steel production balance remains almost constant, with an EAF route production of 17 % in 2015 and 19 % in 2050. This evolution is confirmed by observing that the majority of the investments for the flat steel production are flowing towards new BOF installations, while for long steel the new investments are mostly related to new EAF installation to capitalize on the growing amount of available scrap (see Figure 7 and Figure 8).

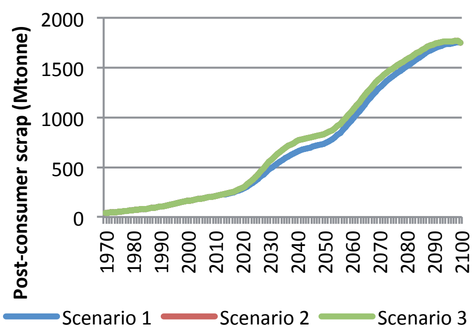


*Figure 4. Post-consumer (LQ) scrap 1970–2100 (Mtonne).*

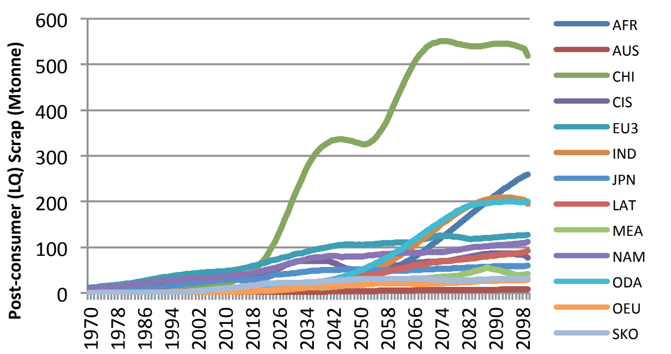


*Figure 5. Post-consumer (LQ) scrap availability per region, Scenario 2, 1970–2100 (Mtonne).*

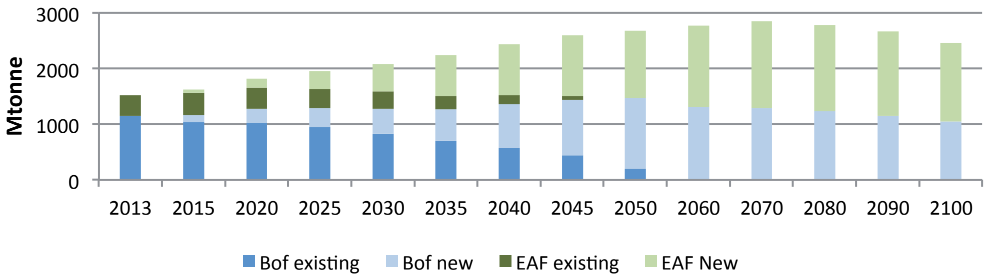


*Figure 6. World steel production by technology (baseline scenario).*

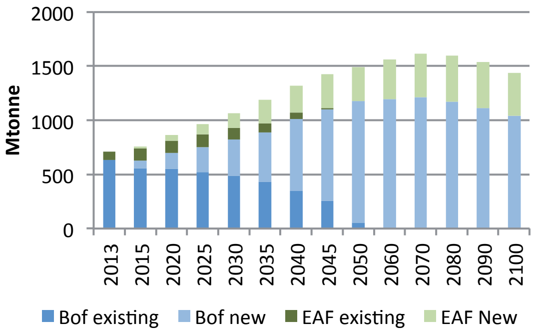


*Figure 7. World flat steel production by technology (baseline scenario).*

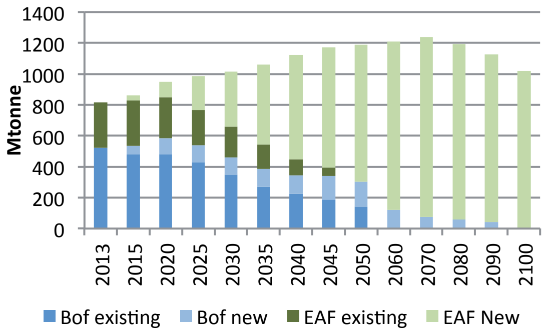


*Figure 8. World long steel production by technology (baseline scenario).*

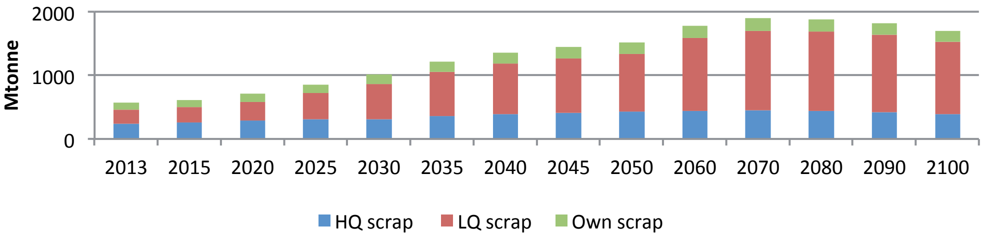


*Figure 9. Global scrap use by type: own, low- and HQ (base scenario).*

In contrast to the global steel production outlook, region-specific projections for the EU 30 show only a moderate growth of 23 % for flat steel production (86 Mtonnes in 2015 and 106 Mtonnes in 2050) and stable production for long products till 2050 (54 Mtonnes in 2015 and 53 Mtonnes in 2050).

Analyzing the model output for flat steel production in Europe in greater detail, we observe that the European demand is strong and stable enough to trigger capital investments in BOF installations within Europe for each observed time period till 2100. Only a small amount of flat steel demand in 2070, 2080 and 2100 is met by imports from other world regions. In the year 2050, 88 % of flat steel production will originate from new BOF installations and approximately 12 % from new EAF installations, using HQ scrap. In Europe, long products will purely originate from the EAF route. New investments in BOF installations are not observed, which is the result of the readily available LQ scrap as raw material input. Similar to the flat steel analysis, it can also be observed that the European demand for long steel is met by European production only. While Europe continues to lose market share in the aggregated crude steel production, as the global growth outpaces the EU 30 growth, one can observe that the steel production industry in Europe remains vital in long and flat steel production in our model.

### SCRAP USE

A major focus of this study is the use and role of steel scrap in the future of the global and European steel production. Figure 9 shows the development of the steel scrap use separated by scrap categories for the baseline scenario. Globally, the use of steel scrap will grow from 611 Mtonnes in 2015 to 1.5 Gtonnes in 2050, a 245 % increase. The three scrap categories will all grow from 259/238/113 to 426/906/188 Mtonnes of usage, for HQ/LQ/own scrap respectively. The highest growth rate can be observed for the LQ scrap category, which increases by 380 % from 2015 to 2050. In the base scenario, the aggregated scrap usage will peak in 2070 close to 1.9 Gtonnes. Comparing this to the results from SAAM shown in Figure 4, the LQ scrap availability in SAAM is slightly lower but, if trade and over-the-year transposition of scrap is taken into account, the results converge.

#### LQ scrap trade

The large amount of LQ scrap available in the market triggers an increasing trade activity among the world regions. As Figure 10 depicts, total global imports of LQ scrap increases tenfold from 40 Mtonnes in 2015 to 432 Mtonnes in 2050. This means close to half of the LQ scrap used will be traded among world regions in 2050 (432 Mtonnes traded of 906 Mtonnes used). The majority of scrap is imported to Africa, India and ODA. This seems quite reasonable, as most economic development till 2050 is projected to occur in these regions, including a high demand for new infrastructure. Such development requires large amounts of long steel. The largest exporter is by far China with 275 Mtonnes in 2050, which is equal to 63 % of the global LQ scrap exports (see Figure 11).

#### HQ scrap trade

The overview for HQ scrap is quite different than what shown previously for LQ scrap. In 2015, the trade is approximately 40 Mtonnes. The development of trade activity is quite volatile; declining to 5 Mtonnes in 2050 (see Figure 12 and Figure 13).

While the group of importing countries is diverse, with India and North America holding the largest share in the projection, the exports are coming from China only. This can be explained by the large (over)capacity in flat steel production which has been created in recent years in China. The model chooses to use the BOF installations capacity over the expected life-time (40 years), because it is economically the most attractive. This results in large amounts of HQ scrap being traded globally from China as production capacity declines.

#### Impact of recycling rates and $CO_2$ tax

The use of scrap appears to be determined by the recycling rates, as well as by $CO_2$ price. Globally, there are two relevant periods (see Figure 14). Up to 2070, all available scrap is effectively recycled into new steel, but from 2070 onwards, excess LQ scrap is only recycled in the low cost variant and when a $CO_2$ price justifies it.

To analyze the impact of $CO_2$ tax, which in this study is considered to be cost incurred per tonne of emitted $CO_2$ during the production of steel, the four scenarios *T15EU, T50EU, T15WO* and *T50WO* were analyzed in addition to the baseline. Reviewing the results, no real impact of $CO_2$ price on the use of scrap is observed at global level until 2050. From 2070 onwards, when global steel production peaks, there is an excess of LQ scrap globally. This global excess of LQ scrap cannot be absorbed by the market, even if emerging countries accept to rely almost entirely on scrap import. Introducing a global $CO_2$ price of €15 (*T15WO*) or €50 (*T50WO*) does increase the use of scrap from 2070 onwards. Interestingly, the effect of combining a €15 tax scheme with the introduction of a new technology to upgrade LQ scrap to HQ scrap has an almost equal effect as a €50 global $CO_2$ tax.

### UP-TAKE OF NEW TECHNOLOGIES

#### Top gas recycling

The top gas recycling technology finds a wide-spread geographical acceptance in the model, even without the introduction of an emission trading scheme as simulated in the baseline scenario. After a slow up-take in its usage, the technology sees an

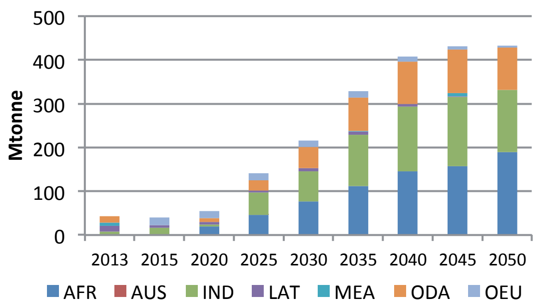


*Figure 10. LQ scrap imports per country (baseline scenario).*

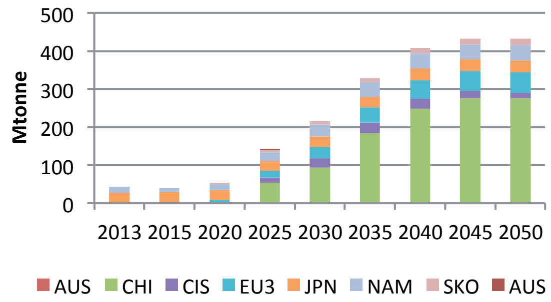


*Figure 11. LQ scrap exports per country (baseline scenario).*

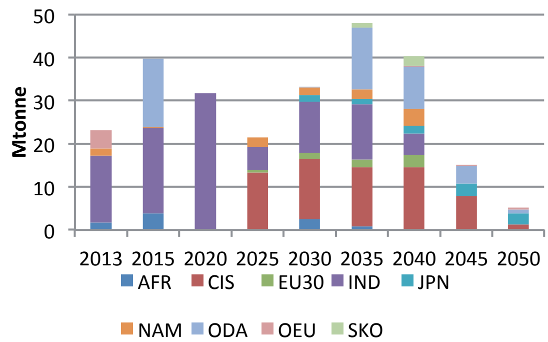


*Figure 12. HQ scrap imports per country (baseline scenario).*

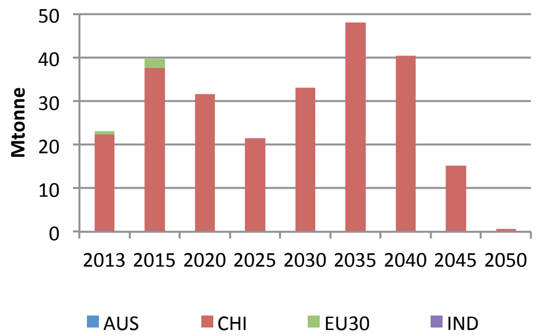


*Figure 13. HQ scrap exports per country (baseline scenario).*

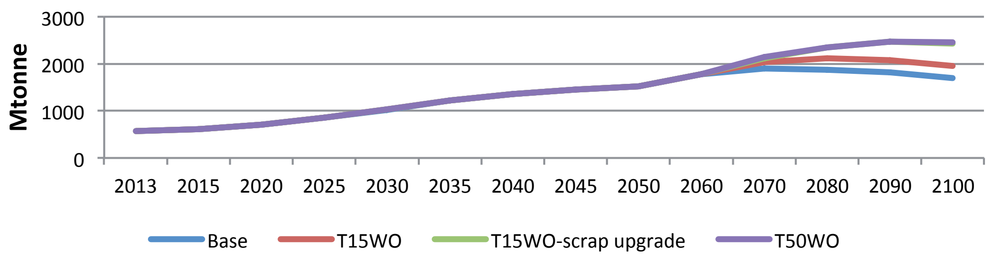


*Figure 14. Sensitivity of scrap use to $CO_2$ price and cost of upgrading.*

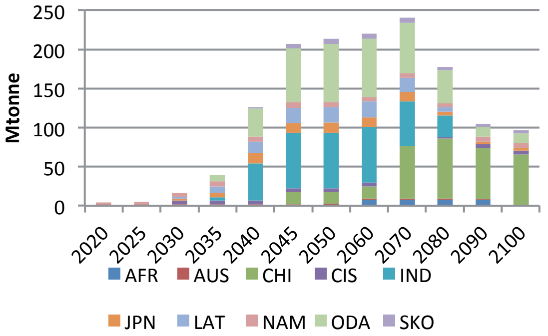


Figure 15. Utilization of top gas recycling according to world regions (base scenario).

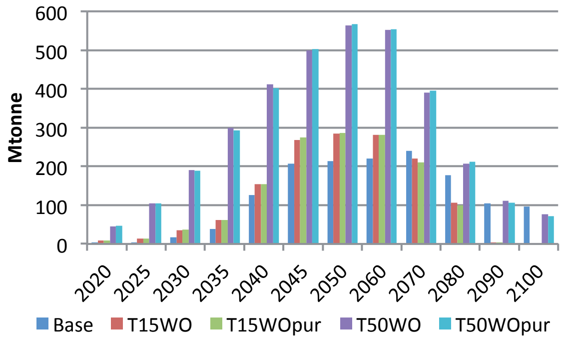


Figure 16. Worldwide utilization of top gas recycling under different scenario conditions.

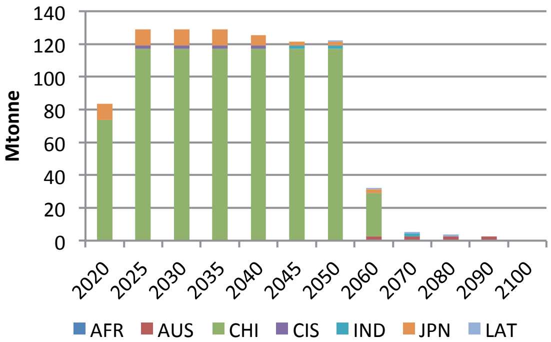


Figure 17. Regional utilization of JET BOF technology in the T15WO scenario.

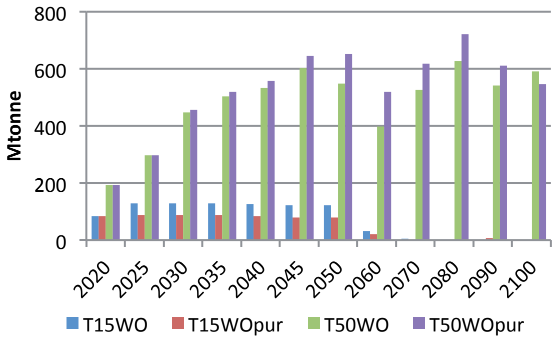


Figure 18. Global uptake of JET-BOF in different scenarios.

intense growth period for 10 years from 39 ktonnes in 2035 to 207 ktonnes crude steel production in 2045 (see Figure 15). Most applications are installed in India and ODA countries, which are the regions with the highest green field investments in BOF production routes.

Since top gas recycling offers significant reduction potential for the input materials coke gas and coal and also electricity, the cost for $CO_2$ emissions has a noticeable impact on the uptake of such technology. Under the T15WO and T50WO scenario the up-take is faster, meaning it occurs earlier in the model horizon, and higher in absolute numbers. By 2050, the amount of steel produced with such a technology would increase under the T15WO scenario from 213 ktonnes to 285 ktonnes (33 % increase) and under the T50WO scenario up to 563 ktonnes (a 264 % increase in uptake) (see Figure 16).

#### JET BOF

With the JET BOF technology, the scrap share can increase up to a 50 % share in the BOF process. A first observation is that the uptake of this technology is not as significant. In the baseline scenario, JET BOF is not selected at all. This can be explained by the fact that when excess blast furnace capacity or integrated scrap availability exist, replacing BOF by JET-BOF is an attractive alternative for scrap utilization. Once excess blast furnace capacity disappears, JET-BOF becomes less attractive. While the dissemination is limited in the *T15WO* scenario, its global usage increases rapidly under the *T50WO* scenario (see Figure 17 and Figure 18). The utilization under the *T50WO* is six-times higher and reaches a level of 600 ktonnes of production.

#### Scrap Purification

The results show that scrap purification, meaning a technology converting LQ scrap to HQ scrap, becomes relevant in a situation with global excess LQ scrap. In our model, we do not consider any trade limitations, and thus local excess scrap easily finds a use elsewhere. The only limiting factor is transport cost. In the "*purification*" scenarios, the cost of purification has been set at a level below transport cost. Under these circumstances it might become attractive to invest earlier in this technology, particularly when HQ scrap becomes scarce, such as in Scenario 3 for reduced HQ scrap availability and/or when a local $CO_2$ tax is applied. In Figure 19, this is illustrated for two scenarios in which 3.5 to 7 Mtonne scrap is upgraded in EU30. These results are to be considered as pure illustrative as the attractiveness of scrap purification completely depends on the cost.

### $CO_2$ EMISSIONS

Figure 20 and Figure 21 give worldwide steel production-related $CO_2$ emissions and the evolution of the specific emissions respectively. The increase in the use of scrap as base material is the main reason for the sharp decrease of the specific emissions, but Top Gas Recycling and JET BOF will contribute as well to the decrease of emissions. In 2050, specific $CO_2$ emissions will be 27 % lower compared to 2013 and, in 2100, this can be 70 %.

#### Impact of a unilateral $CO_2$ tax

A unilateral $CO_2$ tax introduction in Europe at the level of €15 or €50 in line with the scenarios considered will have significant impact on production levels. While the *T15EU* scenario would result in a stable flat production in Europe from 2020 till 2050 (instead of a 15 % growth in the base scenario), the €50 unilateral EU tax (*T50EU*) would lead to a significant reduction in production levels, resulting in only 68 Mtonnes in 2020, declining to 22 Mtonnes in 2050 (see Figure 22). By 2050, this implies only 21 % of the production level in the *T50EU* scenario compared to the baseline scenario. This information is of particular interest to EU policy makers.

## Conclusions

The combination of the Steel Optimization and the Scrap Availability Assessment Model for analyzing the future of steel production globally provides interesting results from several perspectives. Based on geographically disaggregated and estimates of steel demand and scrap availability, the model output improves understanding about the role that secondary routes can play in future steel production, and how different policy options may impact the location of production.

For the *global primary and secondary steel production,* a steady increase in production can be observed, reaching approximately 2.7 Gtonnes of combined long and flat steel production in 2050 and peaking around the year 2070 at approximately 2.8 Gtonnes. The split between global EAF production and BOF production will evolve from a 1:2.5 relation in 2015 (1.16 Gtonnes via BOF versus 0.46 Gtonnes via EAF) towards an almost balanced production split in 2050 (1.5 Gtonnes via BOF versus 1.2 Gtonnes via EAF). In 2060, the production in EAF will exceed the production in BOF globally.

As for the *evolution of the production routes* for long and flat product groups, the analysis shows that the majority of the investments on flat steel production are flowing towards new BOF installations. Meanwhile, for long steel, the investments are mostly going to new EAF installations to capitalize on the growing amount of available scrap. The EAF share in long steel production increases from 38 % in 2015 to 70 % in 2050, while the flat steel production balance remains almost constant with an EAF route production of 17 % in 2015 and 19 % in 2050.

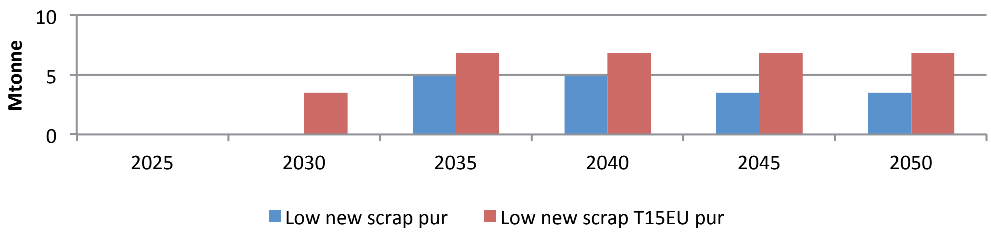


*Figure 19. Scrap purification uptake in EU30 in selected scenarios.*


*Figure 20. Impact of $CO_2$ tax on global steel emissions.*


*Figure 21. Evolution of specific $CO_2$ emissions in steel industry.*

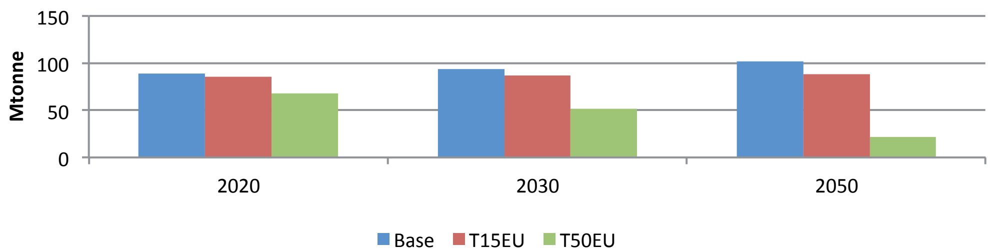


*Figure 22. Impact of a unilateral EU $CO_2$ tax on the EU flat steel production.*

*For the EU,* the study projects only a moderate growth of 23 % in flat steel production (106 Mtonnes in 2050) and stable production levels for long products till 2050 (53 Mtonnes in 2050). Nevertheless, European demand for flat steel is strong and stable enough to trigger capital investments in BOF installations within Europe for each observed time period till 2100. By 2050, long products will purely originate from the EAF route, which is the result of the readily available LQ scrap in Europe. It is important that the necessary policies are introduced while making sure that *carbon leakage* is avoided – the results of the study show that high carbon costs (i.e. higher than €50) may lead to a move of industries from the EU.

Globally, the *use of steel scrap* will grow from 611 Mtonnes in 2015 to 1,500 Mtonnes in 2050, a 245 % increase. The highest growth rate can be observed for the LQ scrap category, increasing by 380 % from 2015 to 2050. The increasing scrap availability justifies the projected deployment of EAF in the future. The large amount of *LQ scrap* available to the market triggers an *increasing trade activity* in the world. In 2050, close to half of the LQ scrap used globally will be traded among world regions (432 Mtonnes traded of 906 Mtonnes used). The majority of low-quality scrap is imported to countries projected to have high economic development until 2050, namely India and countries in Africa and Asia. On the other hand, *trade of HQ scrap* is volatile, never exceeding 50 Mtonnes per year and declining to 5 Mtonnes by 2050. The only exporting country is China, which can be explained by the large (over)capacity in flat steel production resulting from expansion in recent years. HQ scrap is usually exploited immediately and within the plant gates, thus not requiring trade.

Interestingly, secondary production routes will be favored regardless of policy instruments due to their lower costs and higher energy efficiency. That does not mean that primary production routes will cease to exist, as the production of flat steel products will still be predominantly happening in Blast-Oxygen Furnaces (BOF). EAF will be particularly important in the context of developing countries, where the demand for long steel products will be high due to increased infrastructure and construction needs. Introduction of emerging technologies, such as *top gas recycling*, *JET BOF* and *scrap purification* will be facilitated by the introduction of more stringent policy schemes.

To investigate the insights of this study further, improvements of the models used should include the aspect of indirect steel trade in the simulations, as well as improving the estimations for the ratio of long and flat steel products per steel product category and evaluating steel recycling rates at region-specific levels.

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## Appendix

**Table A1. List of world region acronyms used in the Steel Optimization Model and SAAM.**

| | | | | | |
|---|---|---|---|---|---|
| AFR | Africa | EU30 | European Union | MEA | Middle East Asia |
| AUS | Australia | IND | India | NAM | North America (incl. Central America) |
| CHI | China | JPN | Japan | ODA | Other Developing Asia |
| CIS | ex-USSR, excl. EU-30 | LAT | Latin America | OEU | Other Europe |

**Table A2. List of abbreviations.**

| | | | |
|---|---|---|---|
| ASU | Apparent Steel Use | FIXOM | Fixed Operation & Maintenance Cost |
| BIR | Bureau of International Recycling | HQ scrap | High-quality scrap (new or pre-consumer scrap) |
| BOF | Blast Oxygen Furnace | LQ scrap | Low-quality scrap (old or post-consumer scrap) |
| DRI | Direct Reduction Iron | Mtonne | Megatonne (10^6tonne) |
| EAF | Electric Arc Furnace | SAAM | Scrap Availability Assessment Model |
| ETS | Emission Trading Scheme | VAROM | Variable Operation & Maintenance Cost |