Modelling recycling and material efficiency trends in the European steel industry

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Keywords

modelling, climate change mitigation, recycling, material efficiency

Abstract

Analyses and/or scenarios of future industrial production, especially in the field of energy-intensive industries, can be useful for a variety of different task e.g. policy advice, energy demand modelling, resource availability/sustainability, and other. Especially future projection of the physical production differentiated on process level including the modelling of structural change and material strategies are of major importance to generate comprehensive and transparent scenario projections/results. In this context, another challenge is the modelling of this physical production in a hybrid model system, which means to link economic and demographic information provided by a macroeconomic model to the projection of physical production units, e.g. tonnes of an industrial branch. In this paper a short analysis of the historic steel production for selected European countries has been made, selected literature on material efficiency and recycling potentials is reported, and a methodology for the hybrid modelling of future steel use and production on process level as well as scrap availability is described. The paper shows that steel is an old energy-intensive product, facing a decreasing GDP intensity, with a trend to secondary production. This trend to secondary production makes the domestic scrap availability, but also trade in scrap and scrap quality an important factor which has to be considered when modelling future steel production. The developed methodology describes a comprehensive approach to translate macroeconomic sector information, e.g. economic value of an industry (gross value added), into apparent steel use/true steel use of a country and calculate its physical production of crude steel, electric steel, and oxygen steel considering structural change, prompt scrap availability, and end-of-life scrap availability on European level. Finally, limitations of the methods used will be discussed.

Introduction

Tackling climate change by reducing overall energy demand and CO_2-emissions is not only an issue of energy efficiency measures and renewable potentials, which have to be shown and exploited, but also heavily depends on the (inter- and intra) industrial structural changes of a country. Improved material strategies would be an additional option to reduce energy demand and CO_2 emissions, which may lead to higher efficiency in material usage/production and/or increasing substitution with more sustainable materials (e.g. lightweight strategies in the automobile industry) for industrialized countries. In this context, recycling and the use of secondary raw materials play an important role for a sustainable use of natural resources and energy. Jochem et al. (2004) showed that by the year 2004 it was possible to save approximately 150 PJ of energy (i.e. 6 % of present industrial final energy use) in Germany (compared to the frozen material efficiency and recycling level of the 1970s). This example shows that future recycling options, and in this context also future scrap availability are possible adjusting screws in the challenge of mitigating climate change. However, they are also relevant for the industries in terms of production costs, environmental regulations, energy prices, and in a broader context international competitiveness.

Modelling future scrap availability, recycling and steel production on process level can serve several purposes. One example could be the modelling of future industrial energy demand where not only energy efficiency measures and potentials are of crucial importance for the model results, but also the detailed and realistic analysis of the drivers of future industrial energy demand, e.g. physical production in tonnes of energy-intensive basic products. In this context modelling future physical production, material strategies (efficiency and substitution), future recycling options and scrap availability is of major importance to provide transparent and consistent model results (Herbst et al. 2012b; Groenenberg et al. 2005, Jochem et al. 2007, 2008; Schade et al. 2009). Nevertheless, energy demand modelling is not the only purpose modelling of recycling and material efficiency trends can serve. Other examples could be past and current material flow analysis, modelling of future resource availability, etc. For example, Michaelis and Jackson (2000a, 2000b) developed a material flow model for the United Kingdom used to forecast exergy consumption associated with the UK steel sector. For a detailed analysis of different modelling approaches of metal stocks and flows see Müller et al. (2014).

The aim of this paper is to analyse historic trends in the iron and steel industry (steel use, production by process, scrap trade, etc.), to report future recycling and material potentials reflected by selected literature, and to develop a methodological framework for the modelling of future steel production considering recycling, future scrap availability and other changes on material use. The methodological framework of the described modelling approach consists of two basic steps: a regression analysis to identify a behavioural equation for the determination of the apparent steel use in a country, and a material flow approach to calculate future scrap availability and consequently steel production by process.

Steel production routes and scrap availability

Steel is a quality differentiated product – according to the Worldsteel Association (2013c) there are more than 3,500 different grades of steel (e.g. stainless steel, corrosion-resistant steel, heat-resistant steel) with different properties and usages. The transport costs of this heterogeneous product are low in comparison to its value; consequently steel is a highly traded product. In 2012, approximately 414 million tonnes of semi-finished and finished steel products have been exported globally (not including indirect trade of steel), constituting approximately 28.7 per cent of global production (Worldsteel Association (worldsteel), 2013a, p. 23). In the year 2000, steel exports as a share of production reached its historic maximum at approximately 39.2 per cent of global production (Worldsteel Association (worldsteel), 2013a, p. 23).

We categorize steel as an energy-intensive ***final basic product, distinguishing primary and recycle chains of production***. These primary and secondary production routes in Europe are currently mainly covered by two processes: the basic oxygen furnace for the former and the electric arc furnace for the latter. Figure 1 shows the production routes described below in a simplified manner as well as the basic material flows with a particular focus on sources of steel scrap. The following process description has been summarized from Arens et al. (2012). The basic oxygen furnace (BOF) is still the dominating process in the steel industry. The raw materials iron ore and coal are transformed into the basic bulk products sinter and coke via sinter plants in the first case and coke ovens in the latter case. Then these basic bulk products and some additives are further processed in a blast furnace. Iron is produced which is transformed into crude steel in a basic oxygen furnace where oxygen removes the carbon in the iron. This process chain is usually located in integrated steelworks, and often also includes further processing in rolling mills. Steel production in the electric arc furnace (EAF) is an alternative production route. During a simpler one step process steel scrap and some additives are melted in an electric arc as the thermal source. Consequently, this way of producing crude steel is less energy-intensive (Arens et al., 2012, p. 789).

In general, steel scrap can be differentiated into three different types which are distinguished by scrap source: home scrap, prompt scrap and end-of-life scrap or "*post-use scrap*" (Michaelis and Jackson, 2000a; see Figure 1). Home scrap arises in the steel works during the crude steel production and is usually directly fed back into the steel making process. Prompt scrap arises when crude steel is converted into different steel intermediate and final goods (bars, wire, sheets and plates, etc.). This kind of scrap is also recovered immediately and fed back into the production process. End-of-life scrap, on the other hand, arises when goods and products containing steel are no longer used and recovered for the steelmaking process.

Steel is an old basic product, which means that there is very little growth potential for steel demand and production in Europe or North America. The European countries' steel production via the primary route has been either decreasing or stagnating within the last decade. Even though secondary production (via an electric arc) has been growing in some European countries within the last ten years, it is very likely that also this route of production will someday stagnate despite further GDP per capita growth (see Figure 2).

When this will happen depends in the first place on the domestic scrap arising from a country and when it will reach its limits. In this context, the dynamics of future infrastructures (e.g. bridges, railways, buildings) play an important role as it is uncertain when and to which extent refurbishments or additions will take place and enter the recycling process after their specific life times. When these domestic steel cycles approach their limits, the dynamics of the scrap trade among these countries will be the second determining factor, depending on national resources, traditions and company decisions. This hypothetical stagnation of electric steel production (see Figure 2) cannot yet be identified for France, Germany, and Italy (from left to right). The relatively high EAF production in Italy is explained by high net imports of steel scrap (see Figure 5). As shown in the following section countries like Italy and the United Kingdom are very contrary in their production behaviour. While the United Kingdom is an increasing net exporter of steel scrap concentrating its steel production on the oxygen blast furnace route, Italy as a scrap net importer has concentrated on the electric arc furnace route. In general, large countries may change their future specialization in steel production, while small countries prefer not to as they can rely on the smaller production capacities of the EAF route. However, as the BOF route allows to produce high quality steel, countries with substantial investment goods and/or car industries have to also produce by this production route or import high quality steel.

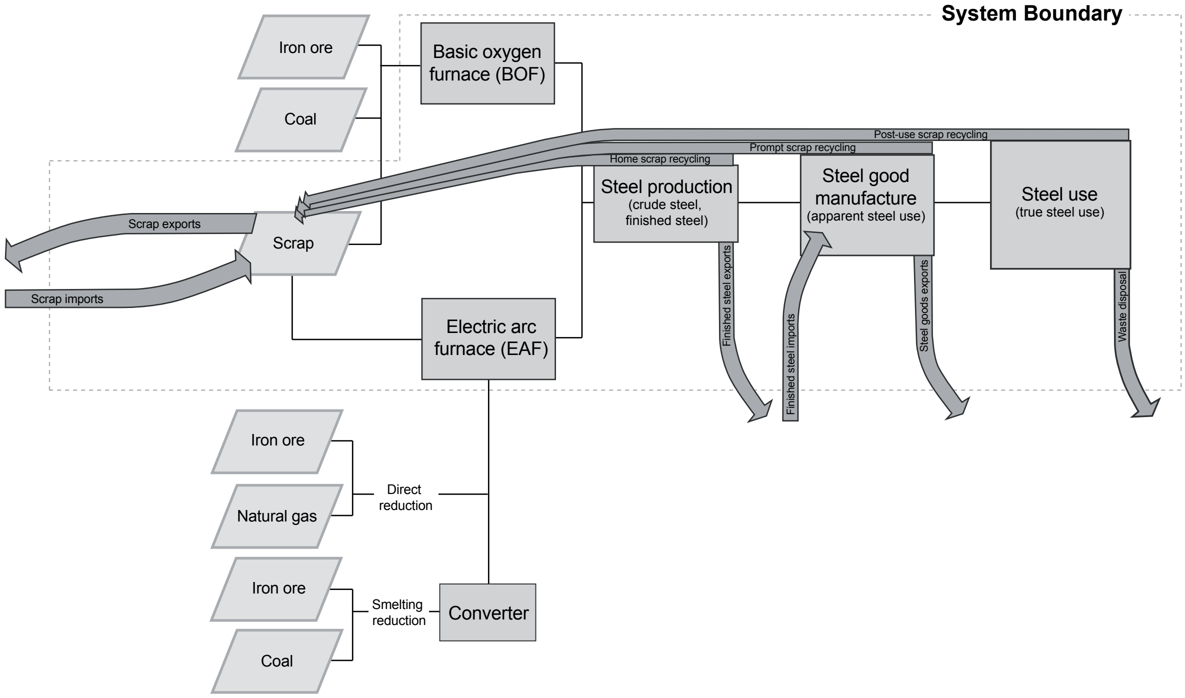

Figure 1. Simplified steel production and material flow process. Source: following Fleiter et al. (2013, p. 279), Michaelis and Jackson (2000, p. 153), World Steel Association (worldsteel) (2012).

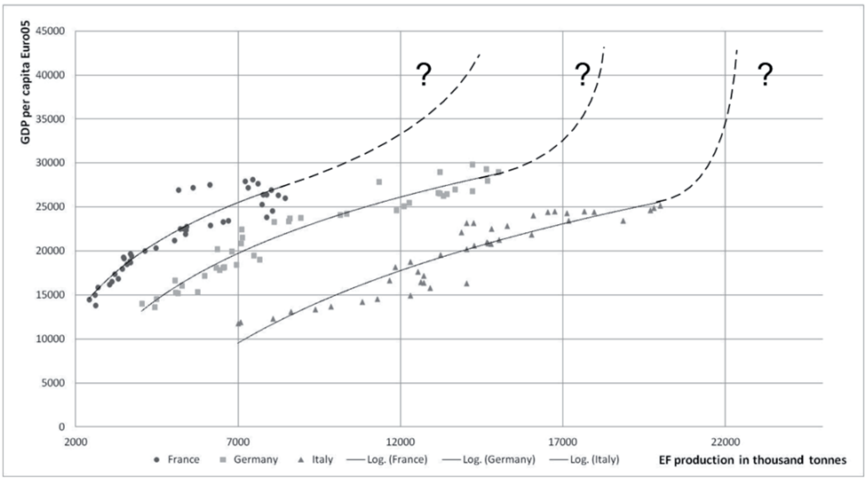

Figure 2. GDP per capita (Euro$_{2005}$) and EAF production (1970–2011) of France, Germany and Italy. Source: The World Bank (2012); World Steel Association (worldsteel) (2013b).

Historic developments in the iron and steel industry

In this section we discuss the production dynamics within the iron and steel industry for France, Germany, Italy, and the United Kingdom since the 1970s (Figure 3). While Germany and Italy have slightly increased their crude steel production within the last decades (except for the crisis 2009) countries like France and the United Kingdom have reduced their crude steel production. One influencing factor for this development might have been the domestic steel demand in France and the United Kingdom. As both countries have lost competitiveness in branches that use steel intensively, like engineering, vehicle construction, and metal products compared to e.g. Germany they had to cut down their steel production.

Another interesting point is the structure of production processes used in these countries, as shown in Figure 4. Germany and France seem to have similar trends in their production structure, with France having a small advantage in the use of the electric arc furnace route (e.g. lower electricity prices). Italy and the United Kingdom seem to be the exponents of the possible production structure development. These differences are supported by the countries' trade in scrap. While Italy has specialised in producing steel via the electric arc furnace route and is a traditional scrap importer (Figure 5), the United Kingdom has increased its net exports of scrap reducing crude steel production and is increasingly using the more energy intensive basic oxygen furnace. Here, the above

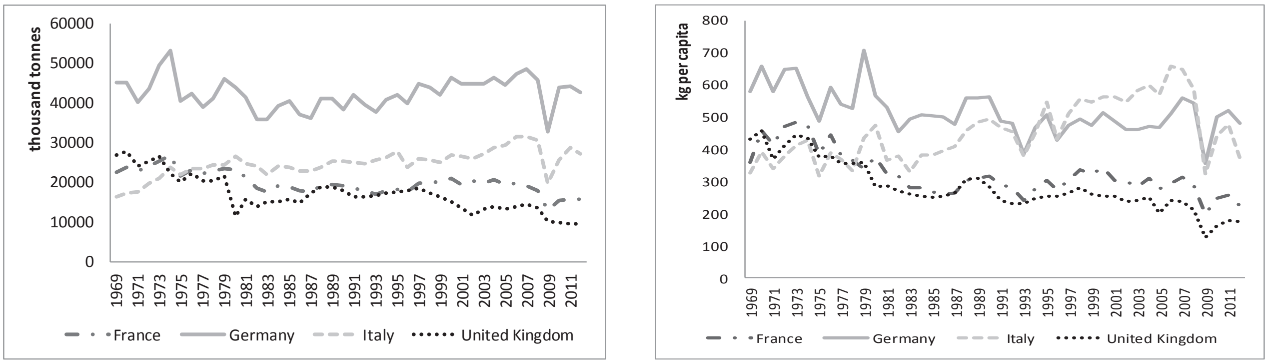

Figure 3. Crude steel production & apparent steel use per capita (crude steel equivalent) 1969–2012. Source: World Steel Association (worldsteel) (2013b).

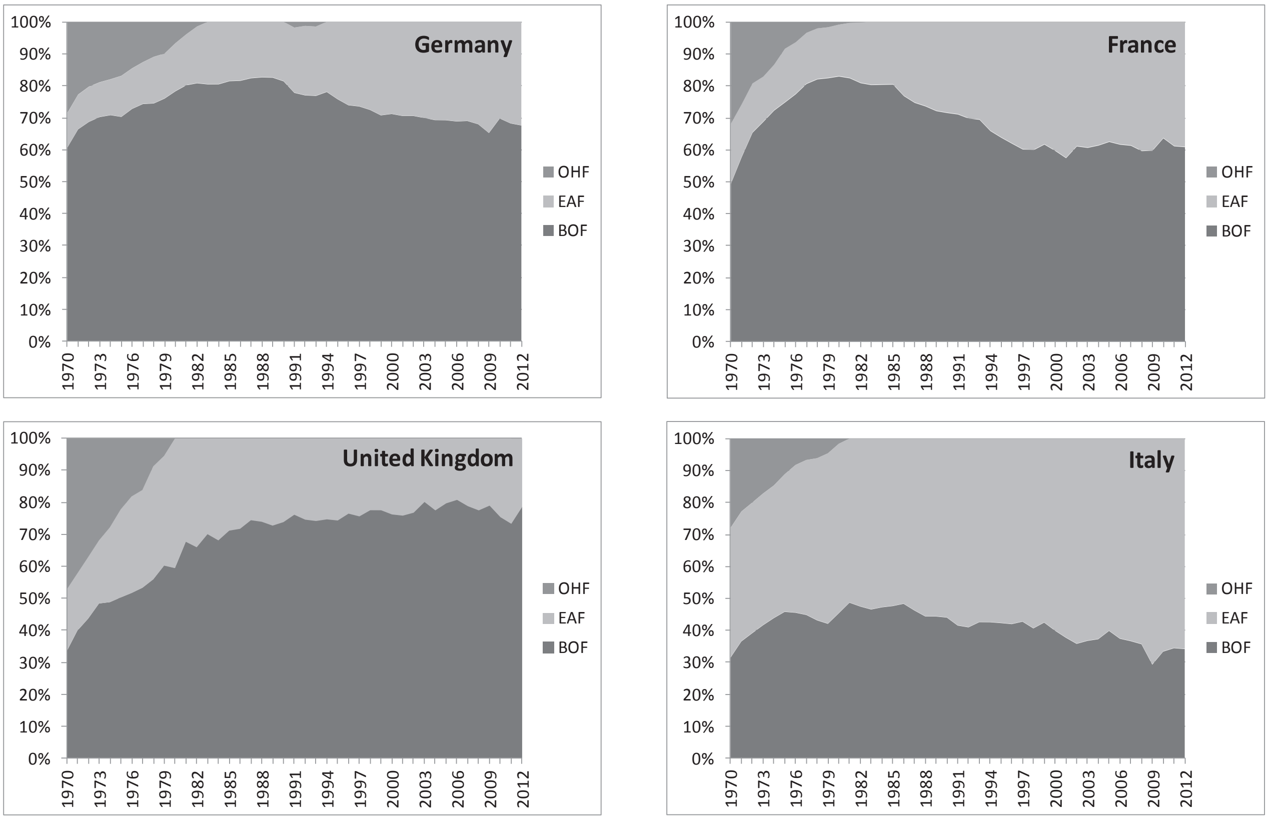

Figure 4. Steel production by process 1970–2012 (percentage share) (OHF: open heart furnace, EAF: electric arc furnace, BOF: blast oxygen furnace). Source: World Steel Association (worldsteel) (2013b).

mentioned argumentation of decreasing competitiveness in countries like France and the United Kingdom is supported by export behaviour and production structure.

Crude steel production per GDP has been steadily decreasing within in the last decades (see Figure 6). This supports the assumption that steel is an old basic product, which means that in order to further increase the value a lesser steel insert in physical tonnes is required. Trends towards higher gross value added (e.g. product accompanying services) and the production of higher quality goods are the drivers for increases in the value added of the industry. This fact is often underestimated when doing energy demand projections, whereby the physical productions are overestimated and consequently also the projected energy demand.

Future recycling and material efficiency potentials

As already mentioned, when modelling steel production, material strategies like e.g. recycling, material efficiency improvement and material substitution have to be considered, aiming to make realistic projections into the future. In the following three studies dealing either with material efficiency or recycling (or both) are presented shortly. Jochem et al. (2004) analyse selected energy-intensive industries (incl. the iron and steel industry) in Germany to identify corresponding saving potentials in production and usage. Milford et al. (2013) analysed the role of material and energy efficiency in the steel industry for greenhouse gas reduction. The World Steel Association (2010) published a fact sheet that outlines steel potentials for reduction, reuse and recycling.

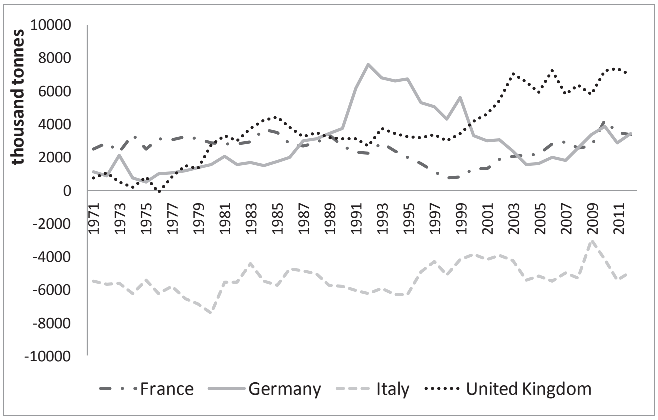

Figure 5. Net scrap exports 1988–2012. Source: Calculated from World Steel Association (worldsteel) (2013b).

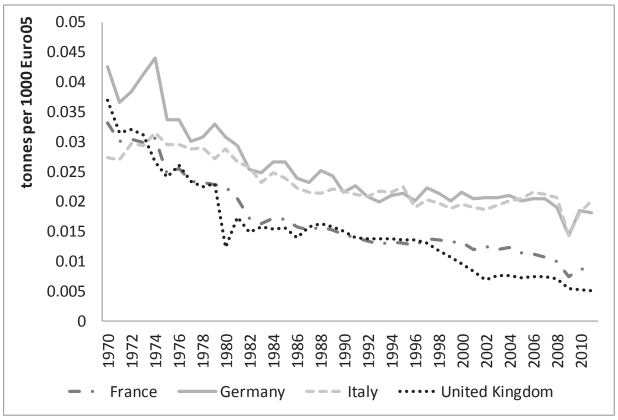

Figure 6. Crude steel production per GDP (thousand Euro 2005, 1970–2011). Source: Calculated from The World Bank (2012), World Steel Association (worldsteel) (2013b).

Table 1. Literature analysis on recycling and material efficiency (potentials).

Author, year of publication	Industry/ Product	Country	Time range	Findings
Milford et al. (2013, p. 3457)	Steel industry	Global	Material Efficiency Strategy Potentials/ Limits	Reuse of post consumer scrap: transport: 0.30, industrial equipment: 0.17, construction: 0.15, products: 0.11. Fabrication scrap diversion: transport: 0.72, industrial equipment: 0.64, construction: 0.00, products: 0.68. Less metal, same service: transport: 0.45, industrial equipment: 0.33, construction: 0.19, products: 0.27. Fabrication yield improvements: transport: 0.10, industrial equipment: 0.06, construction: 0.00, products: 0.09. More intense use: transport: 0.39, industrial equipment: 0.07, construction: 0.40, products: 0.00. Life extension: transport: 0.13, industrial equipment: 0.09, construction: 0.47, products: 0.75.
Worldsteel Association (worldsteel) (2010, p. 2)	Steel industry	World average	2050	Recovery rate per sector: construction: 90 %, automotive: 95 %, machinery: 95 %, appliances: 75 %, containers: 75 %, total: 90 %.
Jochem et al. (2004, p. 42)	Steel industry	Germany	up to 2030	Material efficiency: 1 %/a electronics, engineering, packaging, steel building; 0.4 %/a fabrication, Recycling: 95 % collection quota of new scrap; average life-time of steel products 30 years; old scrap increase from 30 % of produced crude steel to 60 % in 2030.

RECYCLING

Although much data is available on steel scrap and recycling today, there is much uncertainty about the future availability of post consumer steel scrap. While the World Steel Association (2010) projects similar quite high recovery rates at the global level for 2050 (90 per cent) compared to Germany for 2030 (95 per cent), projected by Jochem et al. (2004), the present re-use of post consumer steel scrap at the global level described by Milford et al. (2013) is quite low (max. 30 per cent) as they assume trade-offs with other material strategies (see Table 1).

MATERIAL EFFICIENCY

All three sources emphasize the fact, that material efficiency improvements/innovation can reduce greenhouse gas emissions strongly (Jochem et al., 2004; World Steel Association, 2010; Milford et al., 2013). Milford et al. (2013) also stress the fact that more efficient steel use ("*less metal, same service*") may also substantially influence the steel demand and related steel production. This effect may be partially compensated by the more intensive use of steel (e.g. the trend towards larger cars or higher buildings, fast trains with their substantial demand for tunnels in mountainous countries). Finally, the substitution of steel by other metals or materials may play a role in future steel demand and production. The studies assumptions on material efficiency and recycling are summarized in Table 1.

Modelling changes in recycling and production

In the following, a simple model of recycling and steel production will be described to derive projections for the future physical steel production in tonnes. The major aim of this modelling approach is to translate macroeconomic information (e.g. gross value added) provided by a macroeconomic model into future steel use and project future steel production considering effects of changes in recycling, scrap availability, scrap trade as well as structural change. The model system has been developed for the EU-27 up to 2035 and is still being improved. It is based on earlier works of Michaelis and Jackson (2000a, 2000b) and the Worldsteel Association (worldsteel) (2012). After its finalisation this model will be part of an integrated model system. More information on this model system can be found in Herbst et al. (2012) and Herbst et al. (2013).

SYSTEM BOUNDARIES AND ASSUMPTIONS

The system boundaries of the model are depicted in Figure 1. The following paragraphs describe the underlying modelling assumptions in detail:

I. The model assumes an additional decoupling (to its historic trends) of the apparent steel use in physical tonnes of a country and the gross value added of the steel demanding industries within the country. This means that industries like vehicle construction, engineering, and construction will face a stronger decreasing steel use intensity per unit of value added which can be caused by productivity/material efficiency increases, the use of higher quality inputs (e.g. less waste or burst), or product accompanying services (e.g. maintenance of machinery) that lead to future increases in gross value added not caused/accompanied by increases in steel use. (Herbst et al., 2012, p. 412.)

II. Home scrap: This type of scrap arises directly in the blast oxygen furnace route steelworks and is recycled immediately on site and melted again in the blast oxygen furnace. Consequently, the home scrap accumulated in the oxygen steel plant is not relevant in the electric steel production and can be neglected when calculating the available amount of scrap for electric steel production. We assume the same is true for the electric arc furnace route: all home scrap will be reused immediately at the steelworks.

III. Prompt scrap ratio: In this first modelling approach the "*prompt scrap ratio*" defined by Michaelis and Jackson (2000a) as *"prompt scrap/steel input to manufacture"* will be assumed to remain constant at 15 % (Michaelis and Jackson, 2000a, p. 136). Michaelis and Jackson (2000a) retrieved this information from Chapman and Roberts (1983). Here, more empirical research is needed, which would allow to differentiate this information over time and between countries in the model.

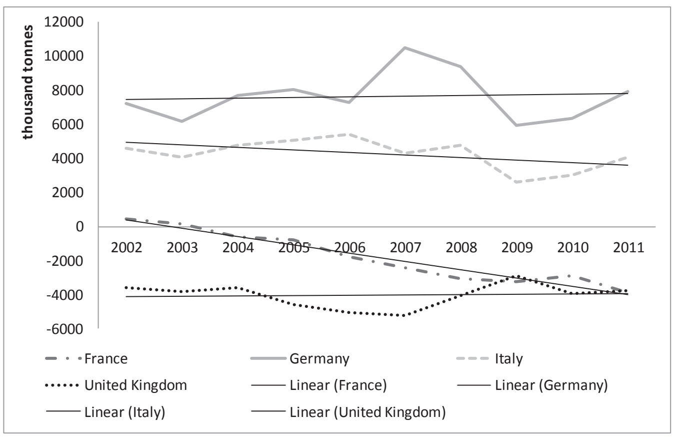

Figure 7. Indirect net exports of steel (2002–2011). Source: World Steel Association (worldsteel) (2013b).

IV. Indirect steel exports: The World Steel Association (worldsteel) (2012, p. 2) describes the indirect trade in steel as "*the trade in steel embedded in cars, ships, machines, white goods and so on, …*". As illustrated in Figure 7 the available time-series of "*indirect net steel exports*" (*IndNX)* (World Steel Association (worldsteel) (2013b) is rather short (nine years). As detailed modelling of trade in goods and machinery is beyond the scope of this paper, as a reliable estimation of future development is difficult according to the length of the times series. As the trend of the indirect net steel exports seem to be rather linear over the sample (except France, see Figure 7), it is assumed that the indirect net steel exports will remain constant on the level of the year 2010 over the models projection horizon.

V. Average life cycle: The average life cycle (alc) of steel containing products has been chosen to be approximately 20 years for all countries over the whole model horizon, which reflects the available literature as shown in Table 2.

VI. Post-use recycled steel scrap: Michaelis and Jackson (2000a, p. 136f) have defined a "post-use recycled steel scrap ratio" (r), or alternative end-of-life scrap recycling rate, which was set to 83 % (Worldsteel Association (worldsteel), 2010; also cited in UNEP, 2013, p. 47) in 2010 for the total steel industry of all countries. This number is assumed to increase linearly up to 90 % until 2035. For the same figure, the Worldsteel Association assumes a world average of 90 % in 2050 (Worldsteel Association (worldsteel), 2010; also cited in UNEP, 2013, p. 47). But as the regarded countries are mostly industrialized countries an achievement of this target until 2035 for Europe is assumed. Here, future improvements will include more appropriate/differentiated setting of r for the year 2035 at country level.

VII. Net scrap exports: Data concerning the historic development of a country's net scrap exports have again been taken from World Steel Association (worldsteel) (2013b) (see Figure 4). As detailed modelling of trade in scrap would be beyond the scope of this paper, it is assumed that the net exports of steel trade will remain constant on the level of the year 2010 over the models projection horizon.

VIII. The EAF-production-scrap ratio λ is assumed remains constant from 2010 to 2035.

IX. The factor μ gives the ratio of crude steel production to the apparent steel use (finished products). This factor is assumed to move linearly towards 1 over the models projection horizon from the level of the year 2010 under the assumptions of decreasing exports of semi-finished products.

METHODOLOGY

In the following the methodology for the projection of the physical production of electric steel and oxygen steel is described, also including assumptions on future scrap availability. The modelling approach consists of two basic steps, a regression analysis to identify future steel use and a "material flow method" to model future scrap availability and steel production.

Table 2. Estimated average life cycle.

Michaelis and Jackson (2000, p. 137)		Wirtschaftsvereinigung Stahl (n/a)** cited in Jochem et al. (2004, p. 23)		Jochem et al (2004, p. 45)		UNEP (2013, p. 47)	
Industry/ Product	**alc**	**Industry/ Product**	**alc**	**Industry/ Product**	**alc**	**Industry/ Product**	**alc**
Construction	30 years	Main construction	50–70 years	Main construction	60 years	Construction	40–70 years
		Steel construction	40–50 years	Steel construction	50 years		
Mechanical engineering equipment	10 years	Engineering	10–25 years	Engineering	20 years	Machinery	10–20 years
Motor vehicles	7 years	Vehicle construction	10–30 years	Transport (vehicle construction)	11 years	Automotive	7–15 years
				Transport (other)	30 years		
Appliances and electrical goods	7 years	Electrical engineering	15–25 years	Electrical engineering	18 years	Electrical and domestic appliances	4–10 years
		Shipbuilding	30–40 years	Shipbuilding	40 years		
Gas, coal, water industries	25 years	Pipework	40–50 years	Pipework	50 years		
Packaging	2 years			Tinplate	1 years		
Other small metal goods	15 years	Metallware (EBM)	1–15 years	Metallware (EBM)	15 years		
Wire manufacture	10 years						
Forging	25 years						
Other	10 years	Other	10–20 years	Others	20 years		
Average lifetime (*weighted)	**14*~15**		**n/a**		**n/a**		**n/a**

*** Data for the year 2000.*

Regression analysis

To identify a behavioural equation for the future development of the apparent steel use of a country and its projection a regression analysis has been made. The definition and concept of a country's "*apparent steel use* (*ASU*)" (finished steel products) has been taken from the Worldsteel Association (worldsteel) (2012) and reads as follows: domestic steel "*deliveries plus net direct imports*" (Worldsteel Association (worldsteel), 2012, p. 2).

For simplification it is assumed that the evolvement of the apparent steel use (ASU) in tonnes finished steel at time t of a country i is dependent on the activity, gross value added (VA), development of the steel demanding sectors j in this country as well as other factors that are not described/explained in this simple modelling approach ($\varepsilon_{t,i}$).

$$ASU_{t,i} = \beta_0 + \beta_j \times VA_{t,j} + \varepsilon_{t,i} \qquad (1)$$

The steel demanding sectors chosen for the analysis are the basic metals industry (*bm.va*), vehicle construction (*veh.va*), engineering (*eng.va*), and construction (*constr.va*).

The data in metric tonnes for 23 countries (Belgium and Luxembourg have been treated as one region) has been taken from the Steel Statistical Yearbooks 2013 to 1987, and the average length of the time series used for the regressions are 1974–2007 for the EU15 countries and shorter for the new member states (Worldsteel Association (worldsteel), 2013b). Value added data has been taken from the EU-KLEMS database for 23 countries (data for Belgium and Luxembourg have been aggregated), the average length of the time-series has been 1974–2007 for the EU15 countries and shorter for the new member states (EU-KLEMS, 2011). This data has been transformed into Euro 2005 using market exchange rates (Bundesbank, 2013).

Table 3 compares the regressions results of an ordinary least squares pooled regression with the alternative method of generalized least squares including time- (TD) and country-dummies (CD) in the regression. As the coefficients of the independent variables of the two methods are the same, the author has chosen the pooled regression for further analysis as there is the possibility to run robust regression and deal with heteroscedasticity. All values except dummies have been natural logarithms. Robust pooled regressions have also been run only considering country-fixed effects (Table 3, equation 3) and only considering time-fixed effects (Table 3, equation 4). As results do not improve substantially equation (1) from Table 3 has been chosen as the behavioural equation for the projection of apparent steel use.

$$\ln ASU_{t,i} = \beta_0 + \beta_1 \times \ln bm.va_{t,i} + \beta_2 \times \ln veh.va_{t,i} + \beta_3 \times \ln eng.va_{t,i} + \beta_4 \times \ln constr.va + CD + TD + \varepsilon_{t,i} \quad (2)$$

Equation for the projection of future apparent steel use in the model:

$$\ln ASU_{t,i} = -5.5839492 + 0.06044579 \times \ln bm.va_{t,i} + 0.20079367 \times \ln veh.va_{t,i} + 0.11207649 \times \ln eng.va_{t,i} + 0.43718149 \times \ln constr.va + CD + TD + \varepsilon_{t,i} \quad (3)$$

An average time-dummy coefficient based on the coefficient of the year 2007 has been used for the projection period.

Material flow method

The material flow modelling approach used to project future scrap availability and steel production is based on methodologies of the Worldsteel Association (worldsteel) (2012) and the material and energy flow model for the United Kingdom by Michaelis and Jackson (2000a, 2000b).

Assuming a trend to higher gross value added, the apparent steel use, derived from the above shown regression based behavioural equation, is multiplied by a structural change ratio α for all countries linearly decreasing over time (see assumption I).

$$asu_{t,i} = \alpha_t \times ASU_{t,i} \quad (4)$$

As described in the previous section, the model assumes that all so called "home scrap" will be immediately reused in the steel mill where it occurs (see assumption II). So the modelling approach starts with the calculation of the available and recovered amount of prompt scrap $Scrap_{prompt}$ within year t for country i via a prompt scrap ratio δ (equation 5). This modelling approach as well as the definition and value of the prompt scrap ratio has been adapted from Michaelis and Jackson (2000a, p. 136), see assumption (III).

$$Scrap_{prompt\,t,i} = \delta \times asu_{t,i} \quad (5)$$

To calculate post-use or end-of-life scrap of the products which reach the end of their life cycle within a year, the true steel use of a country in this year has to be calculated. The definition and concept of a country's "*true steel use* (*TSU*)" (finished steel products) has been taken from the Worldsteel Association (worldsteel) (2012), which defined true steel use as apparent steel use minus net indirect steel exports (*IndNX*) (Worldsteel Association (worldsteel), 2012, p. 2).

$$TSU_{t,i} = asu_{t,i} - IndNX_{t,i} \quad (6)$$

The net indirect exports will be assumed to be constant for the projection period as explained above (IV). In addition net indirect steel exports have to be back casted in this model from 2010 until the year 1990, to calculate the respective true steel use for these years, as there is no historical data available before the year 2002. This is done similarly for assumption (IV) by using constant 2002 values of indirect net steel exports.

To calculate the arising amount of "*post-use/end-of-life scrap*" $Scrap_{eol}$ we again follow/use the "*use phase*" model developed by Michaelis and Jackson (2000a, p. 136f). They define "*post-use recycled steel scrap*" as a function steel demand 20 years (see assumption V, *alc*) ago times a post-use recycling rate *r* (Michaelis and Jackson, 2000a, p. 136f). This methodology has been adapted to the true steel use concept and a post-use recycling rate *r* as well as an average life cycle (*alc*) of steel products has been examined via the literature analysis (see assumption V and VI) and determined for the model horizon.

$$Scrap_{eol\,t,i} = r \times TSU_{t-alc,i} \quad (7)$$

Under assumption (II) the calculated scrap amounts (other than home scrap) are aggregated to the total domestic scrap availability $Scrap_{dom}$ for electric arc furnace steel production of a country i at time t.

$$Scrap_{dom\,t,i} = Scrap_{prompt\,t,i} + Scrap_{eol\,t,i} \quad (8)$$

To calculate the total available amount of scrap $Scrap_{total}$ the netto scrap exports $Scrap_{NX}$ of country i at time t under assumption (VII) are subtracted from the domestic available scrap $Scrap_{dom}$.

$$Scrap_{total\,t,i} = Scrap_{dom\,t,i} - ScrapNX_{t,i} \quad (9)$$

Afterwards the produced amount of steel via the electric arc furnace route $PROD_{EAF}$ in a country i at time t is calculated via an EAF-production-scrap ratio λ under assumption (VIII).

$$PROD_{EAF\,t,i} = Scrap_{dom\,t,i} \times \lambda \quad (10)$$

The crude steel production $PROD_{CRUDE}$ of a country i at time t is calculated via a relation factor μ (IX) multiplied by the former calculated apparent steel use (*ASU*).

$$PROD_{CRUDE\,t,i} = ASU_{t,i} \times \mu \quad (11)$$

Finally the steel produced via the basic oxygen furnace route $PROD_{BOF}$ can be calculated as follows:

$$PROD_{BOF\,t,i} = PROD_{CRUDE\,t,i} - PROD_{EAF\,t,i} \quad (12)$$

Results

In the following exemplary results of the methodology presented above are shown for France, Germany, Italy, and the United Kingdom. Projections start in the year 2010. These results have to be interpreted as draft results as the model is still a work in progress and has to be further developed and improved to provide more reliable physical production projections. Results for electric arc furnace and blast oxygen furnace production had to be interpolated in 5-year steps, as the modelling approach still needs more methodological improvement in the context of true steel use, scrap stocks and trade in scrap. In order to deal with the effects of the economic developments in the past, e.g. the crisis in the year 2009, assumptions had to be made concerning scrap trade and scrap use from domestic stocks for France in 2020 and Germany in 2025 as well as Germany and Italy in the year 2030. This had to be done as economic fluctuations in the past currently have major impacts on the model results as they are directly linked to the true steel use (20 years ago) of

Table 3. Regression results apparent steel use (tonnes finished products equivalent) as natural logarithm.

Independent variables	(1) OLS country-fixed effects time-fixed effects	(2) GLS country-fixed effects time-fixed effects	(3) OLS country-fixed effects	(4) OLS time-fixed effects
Value added basic metals (log)	.06044579** (2.61)	.06044579** (3.10)	.08576527*** (5.06)	-.00464872 (-0.22)
Value added vehicle construction (log)	.20079367*** (7.46)	.20079367*** (8.14)	.23486136*** (8.39)	.4042562*** (8.64)
Value added engineering (log)	.11207649*** (4.85)	.11207649*** (4.91)	.13455388*** (5.69)	.00606869 (0.15)
Value added construction (log)	.43718149*** (8.16)	.43718149*** (9.22)	.52405084*** (9.51)	.33715991*** (6.97)
Austria	1.9210342*** (12.95)	-.12326677 (-1.30)	2.3512053*** (18.75)	
Belgium-Luxembourg	2.2421553*** (15.36)	.1978543* (2.10)	2.6640925*** (20.80)	
Bulgaria	(omitted)	(omitted)	(omitted)	
Czech Republic	(omitted)	-2.044301*** (-29.67)	(omitted)	
Denmark	1.8799734*** (10.03)	-.16432764 (-1.30)	2.4157669*** (16.12)	
Estonia	2.6007885*** (6.96)	.55648749 (1.84)	3.7503551*** (13.36)	
Finland	2.0476993*** (10.92)	.00339832 (0.03)	2.5894536*** (17.15)	
France	2.199825*** (30.41)	.15552398*** (3.99)	2.3360227*** (37.97)	
Germany	2.4117979*** (51.22)	.36749693*** (7.63)	2.4371302*** (46.9)	
Greece	(omitted)	(omitted)	(omitted)	
Hungary	2.4549189*** (10.60)	.41061788* (2.39)	3.153108*** (16.37)	
Ireland	1.7468159*** (6.97)	-.29748509 (-1.60)	2.4919119*** (12.37)	
Italy	2.7277952*** (36.59)	.68349424*** (17.67)	2.8832583*** (40.76)	
Latvia	(omitted)	(omitted)	(omitted)	
Lithuania	2.2234934*** (6.45)	.1791924 (0.69)	3.2553193*** (12.97)	
Netherlands	2.0182299*** (15.11)	-.02607111 (-0.33)	2.3979092*** (21.80)	
Poland	2.9794954*** (18.69)	.93519438*** (8.74)	3.472334*** (27.50)	
Portugal	2.332041*** (11.79)	.28774006* (2.08)	2.9329492*** (18.96)	
Slovakia	2.6265641*** (10.57)	.58226315** (3.11)	3.405096*** (16.54)	
Slovenia	2.623099*** (9.44)	.57879798** (2.67)	3.4906504*** (15.30)	
Spain	2.2753026*** (25.01)	.23100166*** (5.54)	2.4858152*** (31.56)	
Sweden	2.0997888*** (13.49)	.05548782 (0.56)	2.536786*** (19.04)	
United Kingdom	2.044301*** (28.83)		2.1751117*** (33.59)	
Constant	-5.5839492*** (-4.11)	-3.5396482** (-2.92)	-9.7449538*** (-8.40)	-1.6835283** (-2.97)
R2	.98739221	(omitted)	.98521995	.87720172
N	534	534	534	534

Source: own calculations.

t statistics in parentheses; time dummies not shown; p<.05; ** p<.01; *** p<.001* a country, which is the basis for the end-of-life scrap calculations. The model results show that the apparent steel, use as well as the crude steel production, is increasing until 2020 in all countries. In the case of Germany steel use and production is stagnating in the period from 2020 to 2035 (Figure 8). Reason for this development is the underlying macroeconomic data provided by the macroeconomic model ASTRA (Krail et al., 2013) which assumed rather high growth in the major driving sectors engineering and vehicle construction which is passed through to the model results.

Electric arc furnace production (EAF) of the selected countries follows different pathways. Germany's EAF production is very high in the year 2035, while Italy's electric arc furnace production stagnates after 2025 (Figure 9). In France there will be little increase in electric arc furnace production while the United Kingdom continues its historic trends and produces less steel in electric arc furnaces.

These results reflect the strong growth in the steel demanding sectors, combined with the assumptions of an increasing post-use recycling rate leading to higher absolute domestic scrap availability in the selected countries in 2035 (see Figure 10).

Conclusions and Outlook

The paper analysed historic steel production trends and presented a hybrid modelling approach of future steel use and production on process level including the modelling of scrap availability and recycling for the countries of the European Union.

In many Western European countries a trend towards secondary production has been observed in the recent past, increasing the importance of steel scrap as production input within the country's economy. However, unlimited growth in secondary production is not expected and future stagnating secondary production will in the first place depend on the dynamics of future infrastructures (e.g. refurbishment or addition) determining domestic scrap availability and the dynamics of scrap trade among countries.

The developed methodology, based on earlier works of the Worldsteel Association (worldsteel) (2012) and the material and energy flow model for the United Kingdom by Michaelis and Jackson (2000a, 2000b), describes a comprehensive approach to translate macroeconomic information (e.g. economic scenarios of gross value added development) of the major steel demanding industries (basic metals industry, vehicle construc-

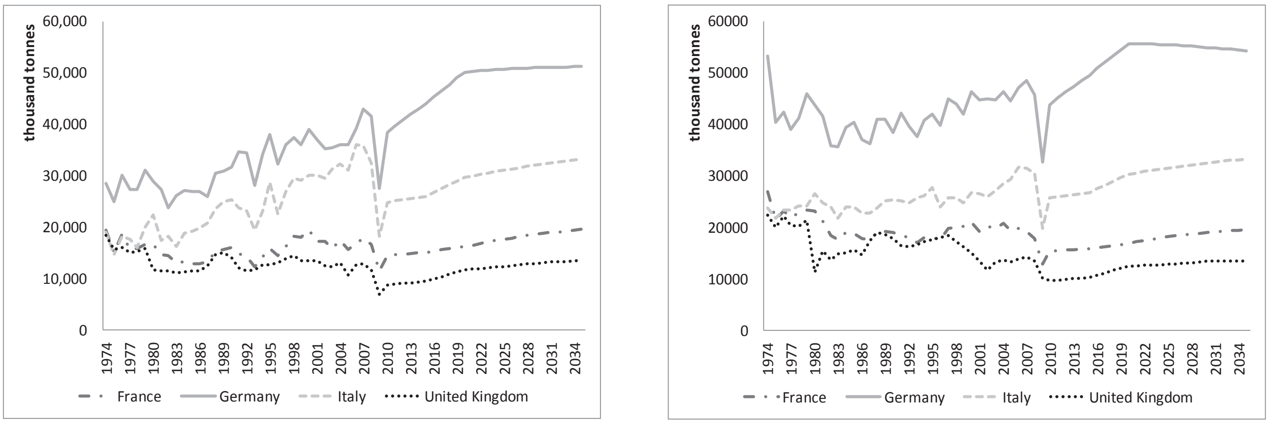

Figure 8. Apparent steel use (finished steel) (1970–2035) & crude steel production (1970–2035). Source: World Steel Association (worldsteel) (2013b) and own calculations.

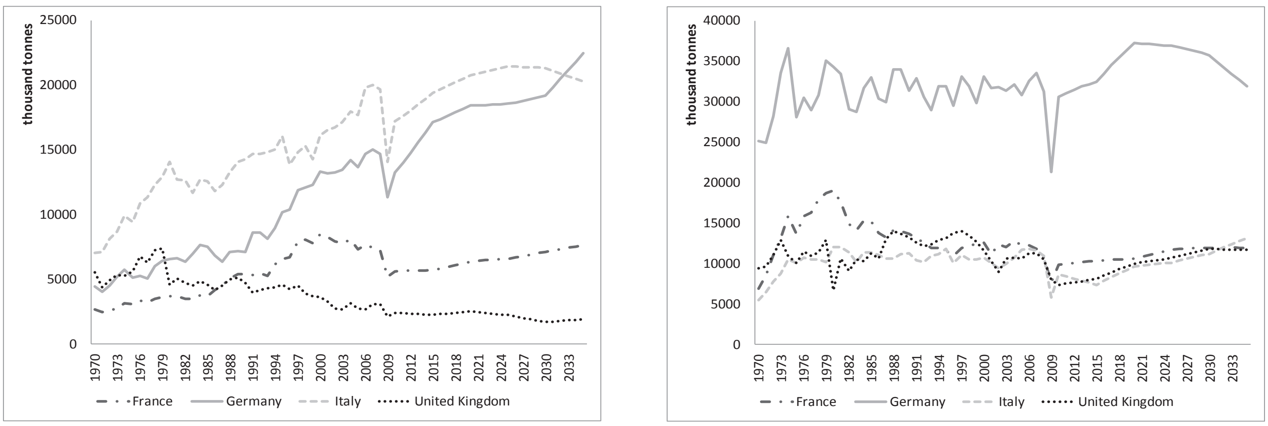

Figure 9. Electric steel production (1970–2035) & oxygen steel production (1970–2035). Source: World Steel Association (worldsteel) (2013b) and own calculations.

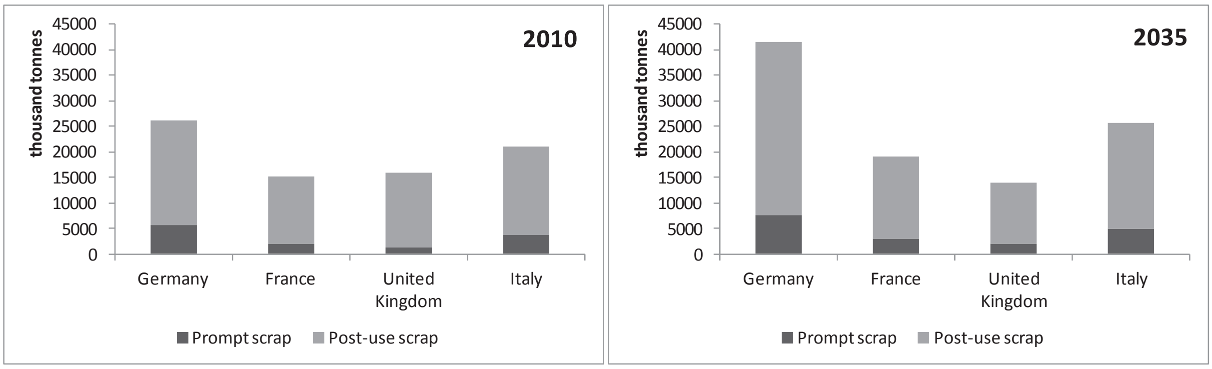

Figure 10. Prompt scrap and post-use-scrap availability (2010 & 2035). Source: World Steel Association (worldsteel) (2013b), Michaelis and Jackson (2000a, 200b) and own calculations.

tion, engineering, and construction) into future projected apparent and true steel use of a country as well as future steel production in physical units electric steel and oxygen steel on European level. The model allows transparent modelling of structural change, scrap availability, and trade behaviour considering various important influencing factors (e.g. structural change ratios, scrap ratios, recycling rates, net exports).

Model results showed that steel use and consequently production in Germany, France, Italy, and the United Kingdom is still increasing until 2020 and more or less stagnating afterwards. This increase in steel use and production is accompanied by an increase in secondary steel production using scrap as major input for Germany and France. Italy, which already produces mainly electric steel, faces its secondary production peak approximately 2025. The United Kingdom will further decrease its secondary production as it has done in the past.

Further model improvements are necessary (and will be undertaken within the next two years) to ameliorate model results. More empirical data on scrap availability and scrap origin would be necessary to improve model calibration and to vary parameters (e.g. prompt-scrap ratio) between countries and scenarios. To deal with the above mentioned direct impacts of economic fluctuations in the past on future end-of-life scrap generation, an improved modelling of future steel stocks will be necessary including improve lifetime distribution functions, saturation effects, etc. Regression results will be improved using different regression techniques and explicit modelling of material efficiency and substitution will be added.

After its finalization the model should be used to calculate comprehensive and transparent scenarios of future physical production scenarios. These scenarios can then be differed not only concerning the economic inputs (inter-industrial structural change, trends to higher gross value added), but also using scenario dependent assumptions concerning prompt scrap ratios, end-of-life recycling rates, and trade in scrap.

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