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Full length article

Steel scrap generation in the EU-28 since 1946 – Sources and composition

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ABSTRACT

A detailed understanding of scrap generation and utilization is needed to target increased material efficiencies and circular economy in the steel industry. In the present paper, the generation and composition of steel scrap (production & forming scrap, fabrication scrap and post-consumer scrap and their composition) in the former territory of the EU-28 have been assessed from 1946 to 2017 by means of Material Flow Analysis. The results reveal that the steel scrap composition in the EU-28 has changed significantly since 1946. Until 1980 scrap generation was dominated by new scrap (mostly production & forming scrap). Today, most of the overall steel scrap is post-consumer scrap. Most of the new scrap consists of fabrication scrap. Taking the presence and tolerance levels of major tramp elements in steel (Cu, Sn, Cr, Ni and Mo) into consideration, a material pinch analysis reveals a surplus of steel scrap with higher levels of tramp elements since the 1990ies. This scrap could only be utilized in the European steel industry by dilution with primary iron sources. At present, this surplus scrap seems to be largely exported as its quantity corresponds well to the net-exports of steel scrap from the EU-28. Transplanting the observed trends of steel scrap generation to emerging economies implies a significant increase in fabrication and post-consumer scrap in these countries in the near future. However, the utilization of scrap at higher rates, particularly post-consumer scrap, will challenge the local steel industry as tramp elements significantly increase along the production, use and end-of-life chain.

1. Introduction

After mineral construction materials, steel is the most frequently used commodity in our society. Global crude steel production amounted to almost 1.9 billion tonnes in 2019, and has doubled during the last two decades (based on World Steel Association, 2020). For the coming years only moderate growth, or even no further growth, in global steel production is expected according to Hatayama et al. (2010), a situation that affluent economies (such the United States or the European Union (EU)) have already experienced for several decades. In the case of stagnant steel production rates, the potential raw material supply of steel producers via scrap is gaining in importance since a higher share of the production can be covered by the scrap available and thus less iron ore needs to be used. Such a situation is not only preferable from a resource point of view, but also from an environmental perspective as steel production from scrap is less CO_2 intensive than from iron ore (according to Broadbent (2016) up to 75% CO_2 reduction) Furthermore, scrap based steel production is also associated with other environmental benefits (e.g., lower eutrophication, acidification and photochemical oxidation) in comparison to primary production (Hu et al. 2014, López et al. 2020).

For US steel production, Zhu et al. (2019) show that in 2014 about two-thirds of the annual production stemmed from scrap, including production & forming scrap, fabrication scrap and post-consumer scrap. For the EU, the share of steel production from secondary resources is estimated to be about 54% (see Fellner et al. 2018, Passarini et al. 2018), with a slightly declining trend in recent decades. At a global level, Cullen et al. (2012) estimated that in 2008 only about 36% of overall steel production was based on scrap.

Although steel flows have been extensively researched at different levels and for different regions and time frames (e.g. Cooper et al. 2020, Hatayama et al. 2010, Klinglmair and Fellner 2011, Müller et al. 2011, Müller et al. 2006, Pauliuk et al. 2013, Wang et al. 2007), works conducted for Europe or the EU are rather limited. Analyses of overall steel flows are available only at a rather superficial level (Fellner et al. 2018, Passarini et al. 2018), although the development of steel stocks for single European countries has been investigated in more detail (Müller et al. 2011, Pauliuk et al. 2013). Data on the amounts of the different “types” of steel scrap generated and utilized (e.g., production & forming, fabrication and post-consumer scrap), their origin with regard to finished steel products, the respective composition with respect to the

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content of tramp and alloying elements as well as the temporal development of scrap generation and composition is largely missing. Today only for Japan such data exists, as intensive research regarding tramp and alloying elements present in steel (including their sources and sinks) has been conducted during the recent years (e.g., Oda et al. 2010; Daigo & Goto 2015; Daigo et al. 2017; Nakamura et al. 2017).

However, in order to assess and understand the potential of steel scrap utilization for substituting primary steel production in the European Union, detailed knowledge about steel production, steel qualities, sectoral steel consumption and the scrap generated thereof is essential. Such knowledge would not only be beneficial for the European steel industry, but is also of global significance as historical trends observable for steel use and scrap generation in the EU-28 might help to indicate future developments of steel flows in other regions of the world (e.g., China, India, Africa).

Hence, the main objective of the present paper is to assess the development of steel flows for the territory of today's EU countries including the United Kingdom (in the following referred to EU-28) for the period 1946 to 2017, focusing on scrap generation (divided into production & forming scrap, fabrication scrap and post-consumer/End-of-life (EoL) scrap) and scrap utilization. Besides the assessment of the total flows of the different types of scrap, a qualitative assessment of the composition of the steel scraps with respect to major tramp elements (sum of Cu, Sn, Cr, Ni and Mo) is conducted and the scrap qualities and quantities determined in this manner are compared to the demand for steel in order to evaluate to what extent the steel portfolio of the European steel industry can be potentially produced out of scrap. Moreover, the question as to whether observable trends pertaining to the steel scrap trade might be explained by the qualities of the available scrap was investigated.

2. Methods

2.1. Material flow analysis MFA

The present study uses Material Flow Analysis (MFA) as described by Brunner and Rechberger (2016) to map the steel and steel scrap flows throughout the territory of the EU-28 for the period 1946 to 2017. MFA generally allows the flows and stocks of materials to be assessed through a system that is defined in space and time. The calculations are based on the law of conservation of matter by using a material balance to compare all inputs, stocks and outputs of a process. Hence, unknown flows can be calculated by the mass balance formula (in the present study, for instance, it is used to calculate the quantities of post-consumer scrap):

$$\sum_{i=1}^{k} \dot{m}_{IN,i} = \sum_{j=1}^{l} \dot{m}_{OUT,j} \pm \dot{m}_{STOCK}, \tag{1}$$

with $\dot{m}$ given in steel mass per time unit. $\sum_{i=1}^{k} \dot{m}_{IN,i}$ represents the total steel input $\dot{m}_{IN}$ of k input flows i, $\sum_{j=1}^{l} \dot{m}_{OUT,j}$ the total steel output $\dot{m}_{OUT}$ of i output flows j, and $\dot{m}_{STOCK}$ represents a potential flow from or to a stock located in the process itself. Otherwise, transfer coefficients can be used to calculate unknown flows, as done in the present work for the quantities of fabrication scrap and the distribution to the End-use sectors:

$$TC_j = \frac{\dot{m}_{OUT,\ j}}{\sum_{i=1}^{k} \dot{m}_{IN,\ i}}, \tag{2}$$

where the transfer coefficient TC_j of an output flow j, $\dot{m}_{OUT,\ j}$ is its mass relative to the total mass input $\sum_{i=1}^{k} \dot{m}_{IN,\ i}$ of k flows i. The transfer coefficients can be calculated based on the same equation if all flows are known, which was not, however, the case in the present study.

2.2. MFA model for steel scrap flows

The overall MFA system for the steel flows in the EU-28 is illustrated in Fig. 1. It is defined by six processes and 14 flows of steel and the temporal and spatial boundaries, which is the territory of the EU-28 in the period from 1946 to 2017. The study presents a static, retrospective top-down model for steel scrap flows where each year (72 years) is analysed separately. Since all relevant flows for the study can be derived from statistical data, we refrained from applying a dynamic material flow approach typically used for analyses over longer times.

To assess the flows of the different types of steel scrap (production & forming, fabrication and post-consumer scrap), only three processes out of the six processes shown in Fig. 1, namely *2. Production of intermediate products, 3. Fabrication of finished products* and *6. Scrap market* were analysed and balanced accordingly. Hence, only the flows indicated in red in Fig. 1 were determined, whereas the black flows are just given for the sake of completeness of the system.

For the process "*2. Production of intermediate products*", and hence also for the flows of intermediate products (IP), altogether 19 intermediates are distinguished and determined according to Cullen et al. (2012) and Zhu et al. (2019), which are summarized in Table 1.

Besides the domestic production of intermediate steel products, imports and exports (summarized as net-import of intermediate products (NIIP)) were considered in the present work. *Production & forming scrap* (PFS) include all scrap generated until the production of intermediate steel products and is thus composed of production scrap from steelmaking and forming scrap from the production of intermediates (rolling and forming). According to Cullen et al. (2012) the amount of forming scrap is generally dominant in comparison to the production scrap arising during steel making.

For the calculation of the *Production & forming scrap* (PFS), reported shares of production & forming scrap in relation to the crude steel amounts produced and formed (Eurostat 1970, 1985, 2002) were used together with information about the share of continuous casting steel production. The introduction of the continuous casting steel production led to a signficant decrease in the share of PFS generated (see Supplementary Information – Fig. A1). To portion the overall quantity of PFS to the different intermediates produced, information about the specific scrap generation of the different production and forming processes presented by Cullen et al. (2012) were used. Details about the intermediate specific PFS rates over time derived in this manner are summarized in the Supplementary information (SI) (Table A2). For the total amount of crude steel produced and formed by the European steel industry, the sum of domestic crude steel production (CrS) and net-import of ingots & semis (NIS) has been used. This simplification with regard to PFS generation (in particular concerning production scrap generation which only arises from domestic production) is justified by the fact that NIS is generally below 3% of CrS (see Table A1 of SI).

The 19 intermediate steel products were distributed to 4 different end-use sectors, subcategorized in 10 end-use sectors. For the calculation of *Fabrication scrap* (FS), sector and intermediate steel product specific material efficiency rates were applied. Similarly, intermediate steel product and sector specific transfer coefficients were applied for the distribution of the steel intermediates to the different end-use sectors. The sectors have been chosen in accordance with the works of the same authors cited above (Cullen et al. 2012, Zhu et al. 2019), which can be found in Table 1.

By balancing the process *6. Scrap market*, the quantity of post-consumer scrap recovered (PoCSr) was determined since all other input and output flows of this process were available - either derived from statistical data (net-import of scrap, scrap recycled) or calculated via transfer coefficients (production & forming and fabrication scrap). Losses of new scrap (PFS and FS) were neglected.

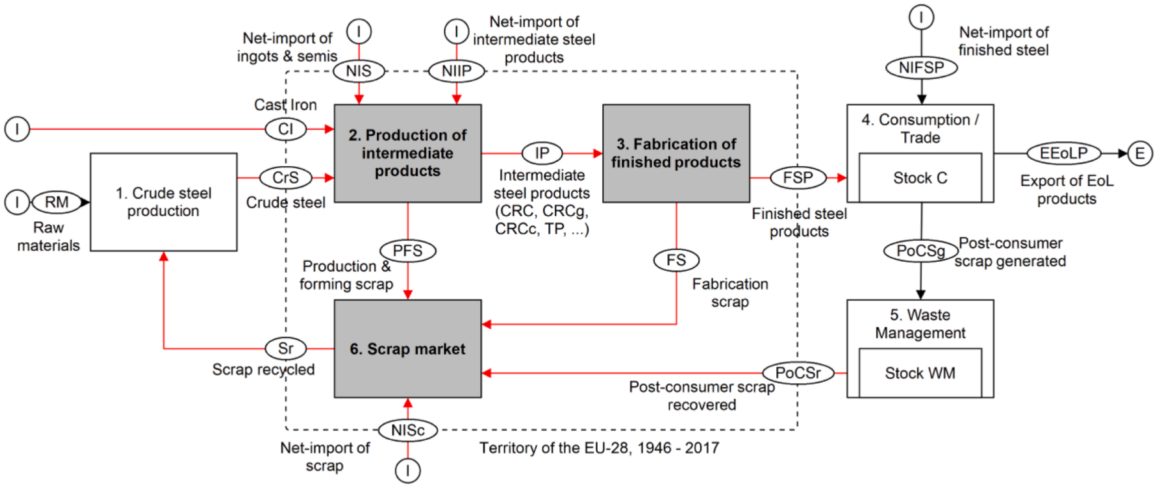

Fig. 1. Simplified MFA system for assessing steel scrap flows in the EU-28 (all red steel flows are determined, whereas black flows are just shown for completeness); the processes 1., . and 5. are also within the borders of the EU-28, but not considered/balanced within the framework of the present study and are hence located outside the system boundary; Stock C ... consumption stock; Stock WM … stock in waste management (e.g., landfills). In addition to steel, the flows of cast iron were considered as well.

Table 1
Intermediate steel products and end use sectors considered (according to Cullen et al., 2012)

Intermediate steel products			**End use sectors**		
Intermediate Steel Products	abbreviation	Grouped Intermediate Steel Products	End Use Sectors	abbreviation	Grouped End Use Sectors
Cast steel	c CS	casts			
Cast Iron	c CI				
Electrical Strip	f ES	flats	Buildings	C Bu	Construction
Tin Plated	f TP		Infrastructure		
Plate (excl. plates used for welded tubes)	f P			C In	
Cold Rolled Coil galvanized	f CRCg				
Cold Rolled Coil coated	f CRCc		Cars	T Ca	Transport
Cold Rolled Coil	f CRC				
Hot Rolled Coil galvanized	f HRg		Trucks	T Tr	
Hot Rolled Narrow Strip (excl. Strips used for welded tubes)	f HRNS		Other Transport	T OT	
Hot Rolled Coil	f HRC				
Welded Tubes	t WT	tubes	Mechanical Engineering	I ME	Industrial Equipment
Seamless Tubes	t ST				
Wire Rod	b WR	bars	Electrical Engineering	I EE	
Reinforcing Bar	b RB				
Hot Rolled Bar	b HRB		Other Metal Goods	MG OMG	Metal Goods
Heavy Section	s HS	shapes	Appliances	MG Ap	
Light Section	s LS		Packaging	MG Pa	
Rail Section	s RS				

2.3. Data sources utilized for steel flows

In the present chapter, the different data sources for assessing the respective steel flows of the MFA diagram are summarized. In particular, the following steel flows are based on statistical data: crude steel, intermediate products, net-import of semis and ingots, net-import of intermediate products, net-import of scrap and scrap domestically recycled, whereas the other flows (remaining red-indicated in Fig. 1) were determined by balancing the single processes or applying transfer coefficients.

Crudesteelproduction(CrS): The total amount of domestic crude steel production was assessed via data published by the World Steel Association. Data for the EU-28 countries (except for Croatia and Slovenia) were available for the period 1967 until 2017. For the years 1946 to 1966 it was assumed that the total crude steel production in the "EU-28 countries" amounts to about 180% (based on the years 1967 - 1972) of the crude steel production of the EU-6. For the latter, statistical data were also available for the early years from Eurostat (Eurostat 1970).

Net-importofSemis&ingots(NIS)andIntermediateproducts(NIIP): The net-import of the semis and ingots and the different intermediates was derived from trade statistics provided by the United Nations Commodity Trade Statistics Database (UN Comtrade 2020) for the years 1994 to 2017 by balancing the trade of semis and the 19 different intermediate products for each member country. For the earlier years (1967 – 1993), only the overall amounts of net-imports of semis & intermediate products (difference between import and export of all steel semis and intermediate products, respectively) were available. For the years before 1972, information about the total net-imports were available for the EU-6, which was used, on the one hand, to assess the share of EU-6 net-imports relative to the total net-imports of the EU-28 (using the years 1967 – 1972, for which data for both, EU-6 and EU-28, were available). On the other hand, the data for the EU-6 were applied together with the aforementioned share to estimate the overall net-import of ingot & semis and intermediates into the EU-28 for the years before 1967. These total annual amounts of net-imports (reported and estimated data) were subsequently distributed to ingots & semis and the 19 different intermediates according to global trade statistics provided by the World Steel Association (International Iron and Steel

Institute 1978). Detailed information about the net-import of ingots & semis and intermediates and their assessment is given in the SI (see Chapter B and Table B1). In general, the net-import of the intermediates amounts to less than ±15% of the domestic production for most of them. Only for a few intermediates (mainly heavy sections, rail sections, and seamless and welded tubes) are higher shares of net-imports in relation to domestic intermediate production observable.

Intermediateproducts(IP): For the domestic production of the different intermediate products (particularly for long products, tubes and selected flat products), data were largely taken from the World Steel Association for the years 1984 – 2017. For the production volume of different flat products in the period 2004 till 2017, information was obtained from Eurofer (Eurofer 2018). It must be noted that Eurofer data were incorporated into the World Steel reporting scheme as they differ for some flat intermediates. For the earlier years, data from the iron & steel yearbooks of Eurostat (Eurostat 1970, 1977, 1985, 1994, 1998, 2002) for the EU-6, EU-9, EU-12 and EU-15 were used to assess the overall production in the EU-28. The production volumes of intermediates reported from the EU-6, EU-9, EU-12 and EU-15 were up-scaled with the respective ratios of crude steel production (e.g., crude steel production in EU-6 referred to crude steel in the EU-28). In order to account for the fact that the production share of the different intermediates in the EU-28 might differ from the data reported for a limited number of member countries (e.g. EU-6), correction factors for the productions volumes of the different intermediates were introduced. These correction factors were derived by comparing the up-scaled production data of intermediates for the EU-28 (based on Eurostat data) with production volumes reported for all EU-28 member countries by the World Steel Association or Eurofer. Detailed information on the annual production of the different semis and the assessment of the data are provided in the SI (see Chapter A and Table A1)

Net-importofscrap(NISc): For the net-import of scrap into the EU-28, data provided in the statistical yearbooks of the World Steel Association were used for the years 1971 - 1987. For the later and earlier years 1988 – 2017 and 1955 – 1970, respectively, data provided by Eurostat were used, whereas for the first decade considered (1946 – 1954), net-scrap imports were estimated assuming that the net-import amounts to about 5% (as observed for 1955 – 1958) of the overall scrap domestically recycled. All data and calculations for assessing the annual net-import of scrap are summarized in the SI (see Table A1).

Scraprecycled(SR): The annual quantity of scrap utilized by the steel industry of the EU-28 countries is reported by the World Steel Association for the period 1967 to 2017. From 1945 to 1966 a constant ratio of 50% for overall scrap consumption in relation to crude steel production was applied, an assumption justified by World Steel data reported for the late ‘60s and the beginning of the ‘70s and which is also in line with data provided by Eurostat on the typical ratio between overall scrap consumption and crude steel production for the EU-6 (Eurostat 1970). Annual data for SR are given in Table A1 of the SI.

Transfercoefficients: Transfer coefficients for the distribution of steel intermediates to specific end-use sectors were derived from different sources (Cullen et al. 2012, EG 1976, 1985, 1990, Eurofer 2018) and have been significantly changing over the last 70 years. For details about the temporal development of the transfer coefficients and their derivation, the reader is referred to the SI (chapter C). For the gross flows of steel intermediates into the 10 different end-use sectors determined in this manner (not displayed in Fig. 1), fabrication losses were assessed. To do so, sector- and semi-specific transfer coefficients for the fabrication scrap (determined by the material efficiencies) provided by Cullen et al. (2012) were applied (see Table D1 of SI). The fact that material efficiencies in the fabricating of final steel goods have improved in recent decades (see Pauliuk et al., 2013) was accounted for (It was assumed that between 1965 and 1995 the material efficiencies for flats and longs increased by 15% and 5%, respectively, see SI – Fig. D1).

2.4. Steel and scrap qualities

In order to assess the qualities of steel and steel scrap, four different levels of major tramp elements (impurities of Cu, Sn, Cr, Ni and Mo) in steel and thus steel qualities were considered (see Table 2). The sum of major tramp elements for assessing steel qualities was preferred over considering single elements, as for many steel grades the sum is limited due to the fact that the different elements may have super positioning effects on the mechanical properties and workability of steel (Kim et al. 2003; Lee et al. 2004; Daigo et al. 2020). Furthermore, detailed information about the actual presence of single tramp elements in different steel grades is not available for the European steel production (unlike to Japan, e.g., Oda et al. 2010; Daigo & Goto 2015; Daigo et al. 2017; Nakamura et al. 2017). Hence, a semi-quantitative consideration of steel and scrap qualities (considering the impurities of Cu, Sn, Cr, Ni and Mo) had to be chosen.

The classification of the four steel qualities was made based on information provided by several studies (Björkman & Samuelsson, 2014; Daehn et al., 2017; Huellen et al., 2006; Toi et al., 1997). Furthermore, it was assumed that the overall maximum content of tramp elements (sum of Cu, Sn, Cr, Ni and Mo) in steel products amounts to about 1.5 to 2.5 of the maximum Cu content allowed, based on Noro et al. (1997) and Toi et al (1997). In alloyed and stainless steel significantly higher amounts of the respective tramp elements are allowed or required. However, for simplicity reasons this fact has been disregarded in the present paper. According to the data of Eurofer, the overall share of alloyed and stainless steels amounts at present to about 20% of total crude production. Until 1990 their share was even below 10%, thereby justifying the simplification made. Moreover, the tramp elements Cu, which in most cases accounts for about 50% of the sum of the tramp elements considered, is also limited in almost all alloyed and stainless steel grades.

For the new scrap (production & forming and fabrication scrap), the steel qualities with respect to the content of tramp elements were assigned according to the intermediates and the respective steel qualities they arise from. With respect to the assignment of qualities to new scrap, it must be noted that in particular for the first 3 to 4 decades investigated, intermediates with higher tolerance levels of tramp elements (e.g. sections, hot rolled bars, reinforcing bars) have also been produced from primary steel and thus might contain lower levels of tramp elements, as assumed in the present paper. Hence, for this period the quantities of the lower steel quality categories (Q3 & Q4) might be overestimated.

For the EoL scrap, it was assumed based on data provided by different studies (Daehn et al., 2017; Davis et al., 2007; Huellen et al., 2006; Pauliuk et al., 2013; Sasov et al., 2003; Toi et al., 1997; Wagner et al., 2012; Willmann et al., 2017) that 40% to 60% of the scrap correspond to quality Q3 (max. content of tramp elements between 0.25% to 0.35%), whereas the remaining quantities of EoL scrap

Table 2

Steel qualities (tolerable content of tramp elements) considered. Detailed information about the assignment of the four quality categories to the different intermediates and their sectoral use is provided in SI, chapter E (Table E1).

Max. content of tramp elements $\sum$ *(Cu, Sn, Cr, Ni, Mo) in %*	**Quality categories**	**Typical steel intermediates**
<0.18	Q1	most flat products (cold rolled coils) – deep drawing quality, interstitial-free steel
0.18 – 0.25	Q2	tubes, plates, hot rolled products in construction, wire rod (other than construction)
0.25 – 0.35	Q3	hot rolled bar, plates (construction), wire rod (construction)
> 0.35	Q4	heavy section, light section, rail section, reinforcing bar, hot rolled bar (construction)

correspond to quality Q4 (tramp elements > 0.35%).

2.5. *Material pinch analysis for steel and scrap flows*

Pinch analysis represents a method that was developed to minimize the energy demand in industries (Linnhoff & Hindmarsh, 1983). In recent decades, the concept has also been increasingly applied to materials flows (Daehn et al., 2017; Ekvall et al., 2014; Hatayama et al., 2012; Hatayama et al., 2009), thereby taking into account the fact that different processes and products require materials with different purity.

In this study, a version of material pinch analysis is used per annum to assess how quality categories of steel scrap and crude steel demand in the EU-28 match. Unlike to similar works done for steel, excess scrap of lower qualities was not only considered to be diluted by primary steel but also exported out of the EU. The latter might reflect more the actual steel scrap management in case of open markets (no limitation of scrap import and exports). The steel scrap exports assessed in this manner were subsequently compared to the officially reported figures on steel scrap trade in order to evaluate whether scrap trade flows observable can be explained by the quality and quantity of steel scrap domestically available.

2.6. *Validation of steel flows*

To partially validate the mass flows of the steel scrap model presented, the steel flows into finished goods were cross-checked with bottom up data. Therefore, production figures of cars and trucks in the EU-28 countries (OICA 2020) were combined with estimates on the average steel content of cars and trucks. For cars, it was assumed that the average steel content increased from about 700 kg in the ‘60s and ‘70s to 900 kg today (Castellani et al. 2017, ICCT 2011, 2020, Todor and Kiss 2016), whereas for trucks (production mix of light, medium and heavy commercial vehicles) an almost constant steel content over the years of about 2,000 kg per truck was assumed. Further information on the validation data is provided in chapter F of the SI.

3. Results

3.1. *Scrap quantities*

3.1.1. *Production & forming scrap*

Production & forming scrap started at a rate of about 7 Million tonnes (Mt) per year in 1946 and peaked in 1974 at 47 Mt/yr (see Fig. 2). Today EU-28's steel industry generates about 15.5 Mt of production & forming scrap per year. The relative scrap generation (PFS to domestic crude steel production plus net import of ingots & semis) amounts at present to about 8.7%, whereas in the 1950s almost one quarter of crude steel production ended up as PFS, indicating a strong improvement in terms of material efficiencies in the steel industry. Since 1970, when continuous casting steel production was introduced (see also Fig. A1 of the SI), significant improvements in the efficiencies are observable. Between 1970 and 1997 the share of PFS (relative to crude steel production) was halved (from 22% to 11%).

3.1.2. *Fabrication scrap*

The overall annual amount of fabrication scrap in the EU-28 countries rose from 3 Mt in 1946 to a maximum of about 33 Mt in around 2007, currently (in 2017) reaching a level of 26.5 Mt. In 2017 the biggest share of FS originates from the processing of Cold Rolled Coil galvanized (31%), followed by Hot Rolled Coil (20 %) and Cold Rolled Coil (11%). In general, the results of the MFA model clearly indicate the dominant role of flat products for the overall production of fabrication scrap (77%) as they are characterized by a significantly lower material efficiency during the fabrication of final goods in comparison to long products (see Fig. 3).

When the fabrication scrap is assigned to the end-use sectors of finished steel products (see SI - Fig. G2), it becomes obvious that the production of cars was responsible for 30% of the overall FS generated in the EU-28 in 2017, although only about 11% of final domestic steel use ends up in cars. Until the 1970s, the share of the car sector in total fabrication scrap was much smaller and amounted to only 8%-15%. The second most important end-use sector of steel regarding the generation of FS in 2017 represents Other Metal Goods (20%) followed by Mechanical Engineering (15%) and Buildings (13%).

The relative share of fabrication scrap (relative to crude steel production) amounts to 17% today (year 2017). This share has increased over time (in the 1950s it amounted to only about 10%) as more flat products are being produced and subsequently processed and manufactured to final goods.

3.1.3. *Post-consumer scrap (End-of-Life scrap)*

Balancing the process, “*6. Scrap market*” allowed the amount of End-of-Life (EoL) or post-consumer steel scrap actually recovered to be assessed. In particular, it was assumed that the sum of production & forming scrap, fabrication scrap, net-imports of scrap and the EoL scrap recovered must equal the total amount of steel scrap utilized by the EU-28's steel industry, whereby all scrap quantities (except EoL scrap recovered) are either known by statistical data or calculated by means of the MFA model presented. The results thereby obtained for EoL scrap recovered show that the quantity increased from less than 5 Mt/yr in

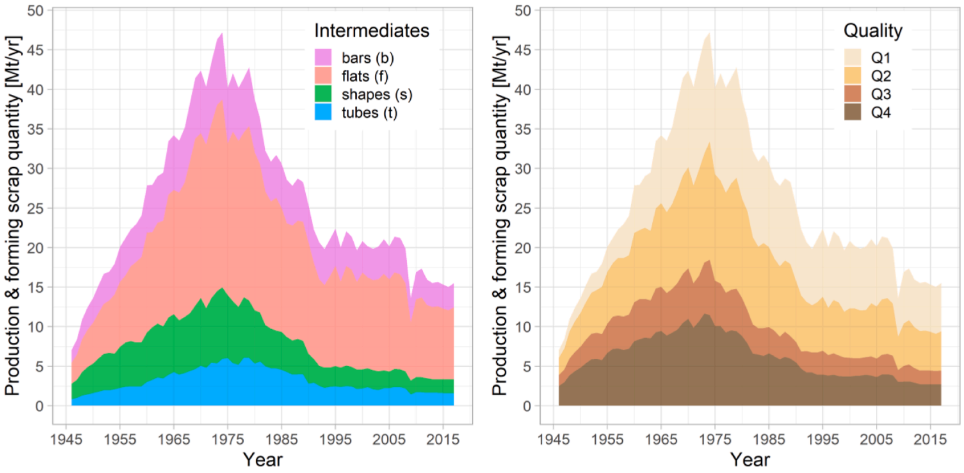

Fig. 2. Annual quantities (given in Mt/yr) of production & forming scrap generation in the EU-28 from 1946 to 2017, categorised by intermediate steel product process (left) and scrap quality based on estimated tramp element contents (right)

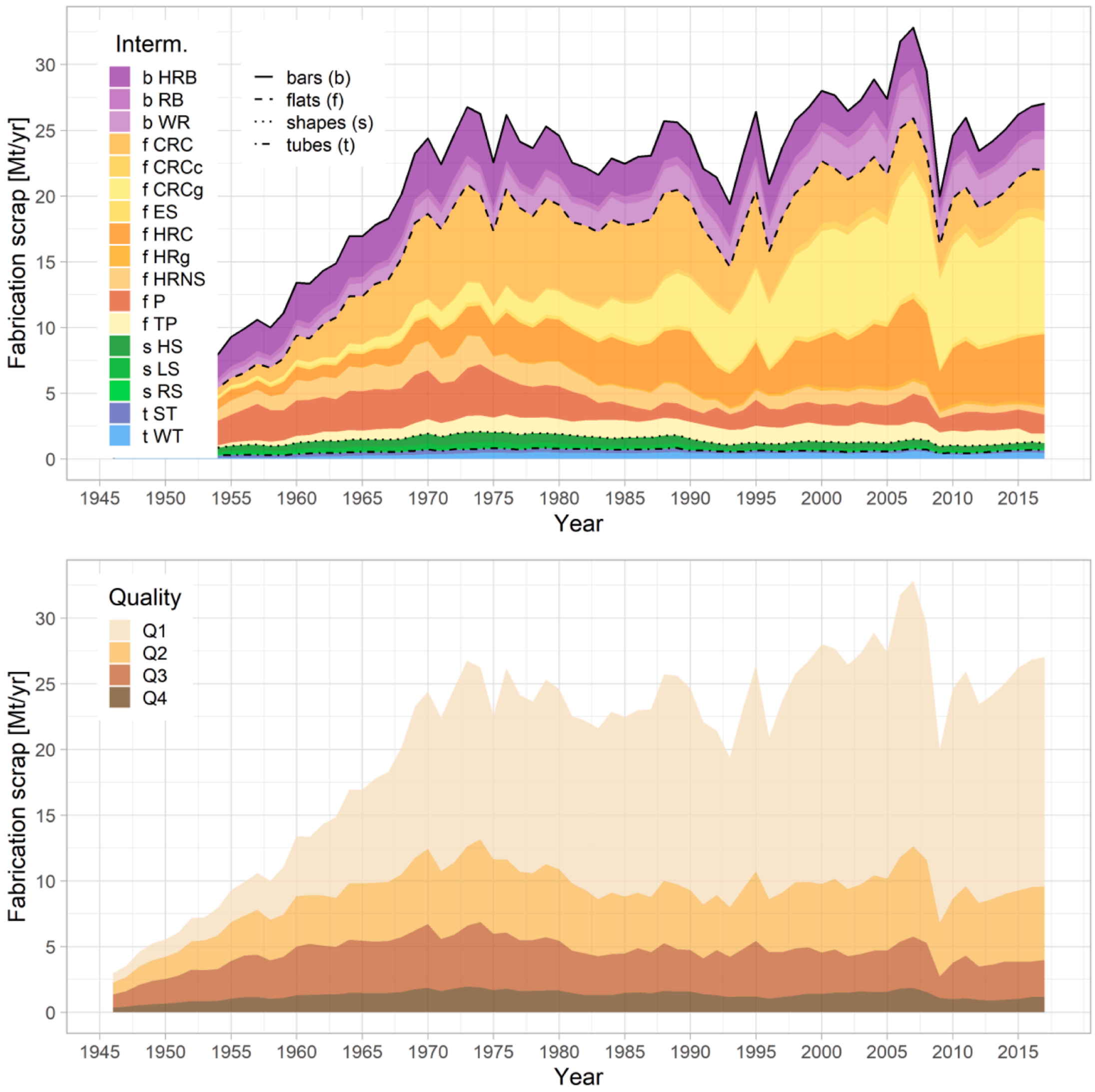

Fig. 3. Annual production of fabrication scrap (given in [Mt/yr]); quantities of fabrication scrap according to the intermediate steel products processed (upper part), according to the resulting qualities (lower part)

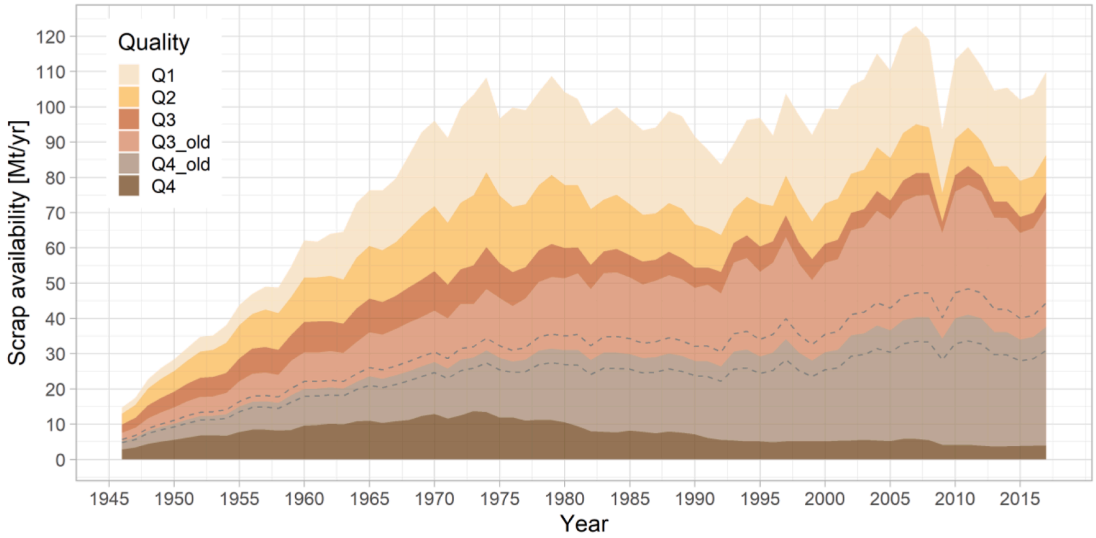

Fig. 4. Annual total of new (production & forming, fabrication) and old (end-of-life) scrap generated (given in [Mt/yr]) categorised by quality. The dashed line indicates possible variability of quality shares for old scrap (40% to 60% to Q3 and Q4, each).

1946 to almost 74 Mt/yr in 2011 (see Fig. 4). In 2017, the EoL scrap recovered amounted to approximately 68 Mt/yr. A steady increase in EoL scrap recovery can be observed over time, which might be interpreted as an indication that the steel stock in the EU-28 is still growing and not saturated yet. EoL scrap not recovered (e.g., lost via landfilling) is not considered in the data presented.

The share of EoL scrap recovered relative to the total scrap utilized increased from about 30% in the early 1950s to more than 70% nowadays, whereby until 1980 the share of EoL was still below 37%. A different trend is observable for the share of production & forming scrap. PFS amounted to more than 45% of the total scrap utilized in the initial years under investigation, while its share dropped to about 17% in 2017. The fabrication scrap share in relation to the total domestically utilized scrap in the 1950s was about 19% and increased to almost 30% in 2017.

3.2. Scrap and steel qualities

Besides the quantities of steel scrap flows, their qualities with respect to the content of tramp elements was assessed as well, taking four different categories into consideration (see Table 2). The results reveal that nowadays the vast majority of the new scrap (PFS and fabrication scrap) can be attributed to quality Q1 (55%) and Q2 (25%), with comparatively low levels of tramp elements (see SI – Fig. E1). Steel scrap quality categories Q3 and Q4 each account for about 10%. Until the beginning of the 60ties, the shares of the four quality categories in new scrap were almost equal.

It was assumed that EoL scrap generated only consists of the categories Q3 and Q4, with possible shares of both categories between 40% to 60%. The overall quantities of the different EoL scrap qualities are displayed in Fig. 4.

Considering the quality categories of crude steel demanded (see SI – Fig. E2), it becomes obvious that also for crude steel a shift towards category Q1 has occurred in recent decades, whereas the shares of categories Q3 and Q4 have continuously decreased. Both observations can be attributed to a shift in the European steel production from long products towards flat products.

The upper part of Fig. 5 provides snapshots of the material pinch analysis by comparing the masses of the different steel scrap qualities (potential material sources for steel) with the crude steel qualities demanded (sinks for the scrap) per annum for selected years. In particular, the masses of steel in each quality category are plotted to visualize the possible destiny of the scrap generated domestically to meet the demand. Until 1960 all scrap domestically generated could be used in steel products with tolerances greater than 0.25 % of tramp elements (category Q3 and Q4). Until the mid-90s scrap supply in the different categories was always significantly lower (at least more than 5 Mt/year) than crude steel demand in the respective quality category. In 1993 and 1994 scrap supply and steel demand for Q3 and Q4 became almost identical. This is also the period when significant net-exports of steel scrap from the EU-28 are observable for the first time (see Fig. 5, lower part). Before this time the EU-28 was a net-importer of steel scrap. For the subsequent years (until 2008) the scrap supply for the categories Q3 and Q4 increasingly surpassed the domestic steel demand in these categories, which corresponds with a growing net-export of steel scrap.

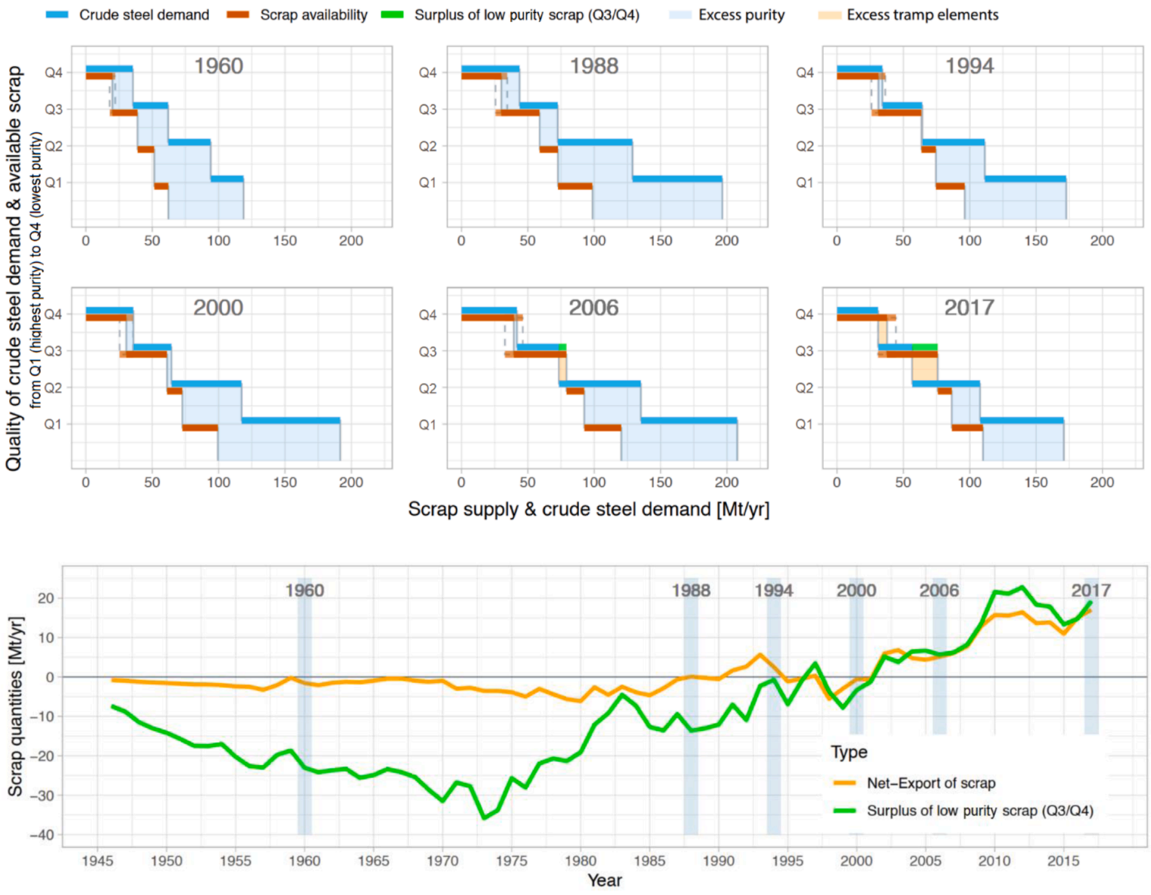

Fig. 5. Material pinch analysis for the quantities and qualities of crude steel demand and available scrap in the EU-28 for the years 1960, 1988, 1994, 2000, 2006 and 2017, orange-shaded areas show the excess tramp elements, blue-shaded areas the excess purities (upper part). Assessed scrap surplus of categories Q3 & Q4 and net-export of scrap from the EU-28 (data are given in Mt/yr). Starting from the time (mid-90s) when a surplus of scrap (positive values) occurred, a good match with the net-export of scrap can be observed (lower part). The overlap between Q3 & Q4 is based on the fact that the assignment of EoL scrap to these classes is uncertain (40% to 60% to Q3 and Q4, each).

From 2009 onwards, the annual amount of “surplus scrap” (for category Q3 and Q4) compared to crude steel demand amounted to 14 to 23 Mt/year. Since that time net-exports of steel scrap peaked and reached a maximum of 17 Mt/yr in 2017.

The temporal trend of the annual amount of “surplus scrap” modelled and the net-export of steel scrap (statistical data) match quite well, which can be seen as an indication that observed exports of steel scrap are mainly due to quality constraints. A detailed analysis of the steel scrap trade (see SI – Fig. E3) confirms that mainly EoL scrap (HS code 720449) is exported, whereas the trade of new scrap (HS code 720441) is largely balanced. The net trade of other steel scrap, such as stainless or alloyed steel scrap (720410, 720421, 720429, 720430), which contain beside new scrap also EoL scrap, is comparatively small.

Instead of exporting the excess scrap of lower purity (Q3 and Q4), diluting it with primary steel sources (e.g., pig iron, directly reduced iron) might be a suitable alternative. In Fig. 5, a comparison of excess tramp elements (shaded in orange) and excess purities (shaded in blue) is shown on a qualitative level (only steel grades are displayed on the y-axis and not the amounts of tramp elements). Comparing the quantities of tramp elements for the year 2017, it becomes obvious that the overall dilution capacity still significantly surpasses the quantities of excess impurities present in the scrap (24 kt/yr of excess tramp elements versus more than 70 kt/yr of excess purities – the respective calculations are provided in the supplementary information; see Table E2). Such a theoretical dilution of impurities, however, is difficult to implement into the steel industry at the European level, given the logistic challenges for scrap management, and the significant changes to current production routes that would be required. Furthermore, it has to be considered that PFS (and to some extent also FS) is obviously recycled at its production plant, thereby limiting the utilization of other steel scrap sources in case of production via basic oxygen furnace.

3.5. Validation of MFA model

The quantitative results of the model were partially validated by comparing the simulated net flows of steel intermediates into finished products, namely cars and trucks, with bottom up data using EU-28 production figures of cars and trucks and their typical steel contents. The results are shown in Fig. 6 and indicate a fairly good fit between model results and bottom up data. Some of the higher steel input modelled for both end-use sectors can be attributed to steel used for maintaining and repairing cars and trucks, which is not covered by the vehicle-based bottom up data used for model validation. Furthermore, the bottom up data are also characterized by a significant uncertainty (estimated to about ±10% for cars and ±20% for trucks, shown as ribbon in Fig. 6) due to limited information about the average steel contents of cars and trucks manufactured in the EU-28 countries and their temporal development.

In general, the outcomes of the comparison verify the assessed distribution of intermediates to the two finished products (cars and trucks) and the respective material efficiencies assumed for the fabrication of these goods. With respect to the scrap modelling efforts, this implies the reliability of the fabrication scrap quantities originating from the fabrication of cars and trucks, which today account for about one third of the overall fabrication scrap generated in the EU-28.

4. Discussion

Besides a tremendous increase in the overall scrap generation from 14 Mt/yr in 1946 to a maximum amount of 120 Mt/yr in 2007, the results further indicate a shift in the composition of the steel scrap generated. Whereas until 1980 most of the scrap generated was new scrap, nowadays the quantities of old scrap generated are dominant. Old scrap accounts for more than 60% of the overall steel scrap recovered in the EU-28. In the 1950s, the share of old scrap was only about 20% of the overall steel scrap generated (see SI Fig. G1).

The observed shift towards higher shares of old scrap in relation to new scrap resulted also in shift towards scrap with higher contents of tramp elements (Cu, Sn, Cr, Ni and Mo). This and the fact that in the EU-28 an increasing share of crude steel is used to produce flat intermediates (mainly driven by a significant increase in the steel end use of the transport sector), which are less tolerant of tramp elements, resulted in a surplus of steel scrap of lower purity in recent decades. This surplus of scrap with lower purity could be tackled by diluting it with new scrap or primary iron sources. Statistical data about scrap trade, however, suggests that the majority of this “surplus scrap” is exported from the EU. During the last decade, the net-export of scrap from the EU-28 amounted on average to about 14 Mt/yr, with EoL scrap representing the vast majority of the exported scrap. Until 1990, when the quantities of scrap with lower purity (Q3 & Q4) were smaller than their domestic demand, the EU-28 countries were net importers of steel scrap. A similar situation for the scrap trade is observable for the United States, where steel scrap is also net-exported to the extent of 9 to 20 Mt/yr or 10 to 20% of domestic steel scrap generation during the last decade, according to (World Steel Association 2018) and Zhu et al. (2019). Steel scrap generation in both the EU-28 and the US are, on the one hand, characterized by a large share of post-consumer scrap (>60%) enriched with tramp elements (e.g., Cu). On the other hand, the portfolio of the steel industry in both regions consists primarily of flat products with lower tolerance levels for tramp elements. Contrary to the EU, the US steel

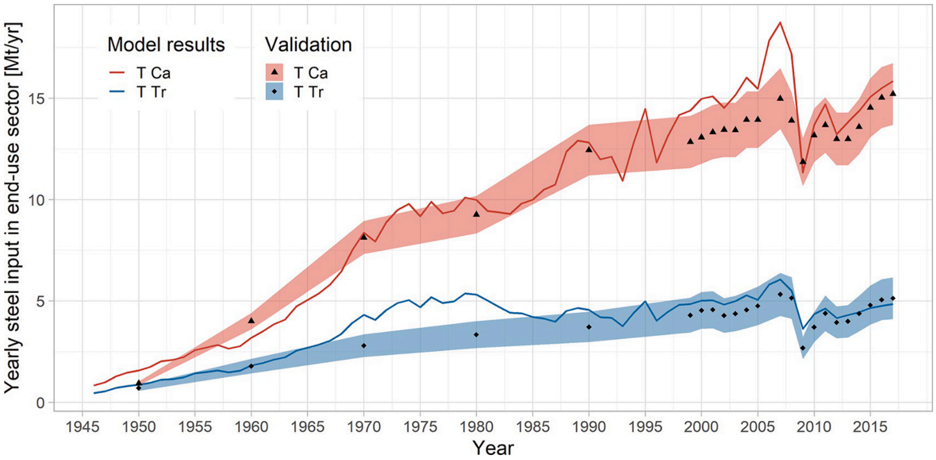

Fig. 6. Comparison of annual steel flows into final cars (T Ca) and trucks (T Tr) manufactured in the EU-28 (model data are indicated by continuous lines; bottom-up data are indicated by dots and ribbons, which indicate the uncertainty of the bottom up data)

industry is capable of producing a significant amount of flat products from electric arc furnace EAF and thus scrap based steel. However, as indicated by Zhu et al. (2019) this EAF steel for flats contains up to 50% of primary iron sources (pig iron and direct reduced iron) in order to control steel scrap impurities.

By comparison, Cullen et al. (2012) determined a share of post-consumer scrap of about 42% (relative to total scrap generation) at the global scale for the year 2008. The ratio of fabrication scrap in their study amounted to 41% and that of production scrap to 17%. In the EU-28 both shares are significantly lower today. 23% of the overall steel scrap generated in the last decade was fabrication scrap and 15% represents production & forming scrap.

Comparing the global shares of the different types of steel scrap to the historical development of scrap generation in the EU-28 countries, the situation in the EU at the beginning of the 1980s is somewhat comparable with the global situation in 2008. In addition, the distribution of steel semis to the different end-use sectors in the EU-28 40 years ago is also comparable to that of the global steel cycle in 2008. Hence, on the simple assumption that historical trends of steel use in Europe are similar to the ones at the global level in the near future, a global surplus of steel scrap with lower purity might be expectable in the coming 30 to 50 years, which is in line with results presented by Daehn et al. (2017). Scrap of this quality (with higher levels of tramp elements) is difficult to recycle without diluting it with primary steel. Today the surplus of old scrap generated in the EU-28 and in the US is counterbalanced by the international scrap trade. This, however, will not be feasible in the future if a global surplus of scrap with lower purity is produced. Hence, to improve the (domestic) circularity of steel, which is targeted by the EU circular economy package, a better separation of post-consumer scrap is mandatory (Daehn et al. 2019). Automated alloy sorting of old scrap or parts of steel-containing products, such as done in the case of EoL vehicles investigated by Ohno et al. (2015) and Willmann et al. (2017), seems to be capable of not only closing the circle of steel, but of saving valuable alloying elements present in old scrap. In addition, several technical interventions might be considered, such as the chemical removal of tramp elements from the melt (e.g., vacuum distillation, sulphide slagging) or redesign of production processes (e.g., direct strip casting (Spitzer et al., 2003)) and materials (e.g., adding interaction alloys for contra balance unfavourable properties) for a higher tolerance of tramp elements (Daigo et al., 2021). Due to practical (e.g., high energy demand, high investments costs) and technical (e.g., only prototypes or lab scale plants realized) barriers, the use of above-mentioned interventions is rarely employed so far.

The results of the study clearly indicate that higher recycling targets for steel products, as demand by the Circular Economy Action Plan of the European Union, (EC 2020), might not necessarily lead to a reduced consumption of primary iron sources in the EU, as quality constraints already today limit the domestic utilization of scrap. Hence, policy makers should consider such quality constraints, which are observable also for other commodities to be recycled at higher rates (e.g. aluminium, plastics). Besides regulating recycling rates, substitution rates should increasingly be incorporated into policies for an enhanced circular economy (see Fellner and Lederer (2020)).

5. Conclusion

The simplified MFA model for steel scrap flows presented allowed the different types of steel scrap generated (incl. their quality with respect to the content of tramp elements) in the EU-28 countries since 1946 to be assessed. Even though more precise modelling of tramp elements in steel flows, as was carried out for Japan (e.g., Oda et al. 2010; Daigo & Goto 2015; Daigo et al. 2017; Nakamura et al. 2017), would be favourable, the following can be concluded from the results of the present study:

A shift in scrap composition (towards EoL scrap and thus scrap with higher contents of impurities) can be observed over the last 75 years. At the same time, more flat steel products, which are less tolerant of tramp elements, are produced within the EU-28. Hence, since the 1990ties a surplus of scrap with higher contents of impurities can be observed which would need dilution with crude steel or primary iron sources (such as direct reduced iron) to be utilized by the European steel industry. At present however, a significant share of the scrap with lower purity is exported from the EU-28, rather than diluted with steel sources with low impurity levels.

In order to domestically recycle a higher share of steel scrap, i) the dilution potential should be exploited, ii) better post-consumer scrap separation (e.g., alloy sorting) and iii) advanced ferrous metallurgical processes (e.g., vacuum distillation, sulphide slagging) are required. The latter would not only facilitate the circularity of steel but would also allow for the recovery of valuable metals (Cr, Ni, Mo, Cu), which are currently non-functionally recycled, as demonstrated by Daigo et al. (2020).

CRediT authorship contribution statement

Sabine Dworak: Conceptualization, Data curtion, Investigation, Formal analysis, Visualization, Writing – original draft. **Johann Fellner:** Conceptualization, Supervision, Data curtion, Writing – review & editing.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105692.

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