20/2021
Dworak, S.; Fellner, J. (2021) “Potential and challenges of steel scrap recycling – a detailed analysis of the european scrap arisings and its quality”, In: Proceedings “Sardinia 2021, 18th International symposium on waste management and sustainable landfilling”, E-paper 1364, CISA Publisher, Forte Village, S.M. Di Pula, Sardinia, Oct. 11th-15th 2021.

SARDINIA2021 HYBRID EVENT / 11-15 OCTOBER 2021 / CAGLIARI / ITALY
18TH INTERNATIONAL SYMPOSIUM ON WASTE MANAGEMENT AND SUSTAINABLE LANDFILLING

POTENTIAL AND CHALLENGES OF STEEL SCRAP RECYCLING – A DETAILED ANALYSIS OF THE EUROPEAN SCRAP ARISINGS AND ITS QUALITY

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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 study, the generation and composition of steel scrap (production & forming scrap, fabrication scrap and post-consumer scrap and their composition) in the territory of the former EU-28 have been assessed from 1946 to 2017 by means of Material Flow Analysis (MFA).

The 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. A tremendous increase in scrap generation and a shift in scrap composition from predominantly new scrap to predominantly old scrap can be observed over the last 75 years. This shift also results in an increasing share of scrap with higher contents of impurities (tramp elements). At the same time, more and more flat steel products, which are less tolerant of tramp elements, are produced within the European Union. Therefore, to utilize all of the domestically available steel scrap (also that of which contains higher amounts of tramp elements), and thereby increase the EU´s substitution rate for primary iron sources to 65% (today the rate amounts to 55%), would require dilution with crude steel that contains lower amounts of tramp elements (such as new scrap or steel from primary sources). At present however, a significant share of the lower quality scrap is exported from the EU-28, rather than diluted with steel sources with low impurity levels.

The global steel market (e.g., share of the different steel intermediates, scrap sources) of 2008, resembles the European one from the early 1980’s. With the assumption that the development of the global market will follow that of the European one, then a global surplus of lower quality scrap might arise in the coming decades. Hence, a more sustainable management of steel scrap is required, which not only includes advanced ferrous metallurgical processes (e.g., vacuum distillation, sulphide slagging), but also needs to address better post-consumer scrap separation (e.g., alloy sorting). 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.

Keywords: Steel, Production & Forming Scrap, Fabrication Scrap, Post-consumer Scrap, Material Flow Analysis, Scrap Quality

1. INTRODUCTION

After mineral building materials, steel is one of the most used commodities. It is used widely in all end-use sectors and experienced extensive growth in the past decades nearly doubling steel production globally (World Steel Association, 2020). In affluent regions, such es the US, the EU or Japan, the steel stock is mostly saturated and no more growth is expected (Hatayama et al., 2010; Müller et al., 2011; Pauliuk, Milford, et al., 2013). This means increasing quantities of end-of-life scrap, while the quantity of crude steel production is stagnated, which calls for higher scrap rates use in steel production. This circumstance is not only beneficial from a resource point of view, but potentially also leads to environmental benefits, such es lower CO_2 emissions, lower eutrophication, acidification and photochemical oxidation compared with steel production from primary resources (Broadbent, 2016; Hu et al., 2014; López et al., 2020).

There are various studies published to investigate steel flows (e.g., (Cooper et al., 2020; Cullen et al., 2012; Hatayama et al., 2010; Müller et al., 2011; Pauliuk, Milford, et al., 2013; Pauliuk, Wang, et al., 2013; Zhu et al., 2019)), but studies on the European level are rare. Regarding the implications of scrap usage in steel production (in form of tramp elements), various studies are available to investigate the possible consequences (process and product wise) and possible technical interventions (e.g., (Daehn et al., 2019; Daigo et al., 2021; Noro et al., 1997; Sampson & Sridhar, 2013; Savov et al., 2003; Spitzer et al., 2003)). But only view studies are available, which quantify the tramp element flows in the system and put it in relation with the crude steel demand (e.g., globally for Cu (Daehn et al., 2017), for Japan (Igarashi et al., 2007)).

The objective of the present study is to quantify the steel flows with their according tramp element contents (sum of Cu, Sn, Cr, Ni and Mo) and compare them with the required qualities of crude steel production to assess the possible scrap rate for steel production and current handling of steel scrap flows.

2. MATERIAL AND METHODS

2.1 Material Flow Analysis (MFA) model for steel scrap flows

MFA (Brunner & Rechberger, 2016) is a widely used method to investigate sources, stocks, and sinks of materials, as well as their connecting flows. It is based on the principles of mass conservation, using a material balance to compare all inputs, stocks and outputs.

The deployed model (Figure 1, adopted from Dworak & Fellner (2021)) represents the steel industry including all territory of the former EU28, from the year 1946 to 2017, considering carbon steel flows. The model is defined by 6 processes (1. Crude steel production, 2. Production of intermediate products, 3. Fabrication of finished products, 4. Consumption and trade, 5. Waste management. 6. Scrap market) and 14 flows (Cast Iron (CI), Crude steel (CrS),Export of EoL products (EEoLP), Fabrication scrap (FS), Finished steel products (FSP), Intermediate steel products (IP), Net-import of finished steel products (NIFSP), Net-import of intermediate steel products (NIIP), Net-import of ingots & semis (NIS), Net-import of scrap (NISc), Production & forming scrap (PFS), Post-consumer scrap generated (PoCSg), Post-consumer scrap recovered (PoCSr), Raw materials (RM), Scrap recycled (Sr)), whereas only 3 of the processes are required to assess the defined steel scrap flows (production & forming scrap, fabrication scrap and post-consumer scrap). The considered processes are shown in grey, the calculated flows in red. The remaining processes and flows are shown for the sake of completeness.

The model is built up in multiple layers. All flows are assigned to one of 19 intermediate steel products (casts - Cast steel (c CS), Cast Iron (c CI); flats - Electrical Strip (f ES), Tin Plated (f TP), Plate (excl. plates used for welded tubes) (f P), Cold Rolled Coil galvanized (f CRCg), Cold Rolled Coil coated (f CRCc), Cold Rolled Coil (f CRC), Hot Rolled Coil galvanized (f HRg), Hot Rolled Narrow Strip (excl. Strips used for welded tubes) (f HRNS), Hot Rolled Coil (f HRC); tubes - Welded Tubes (t WT), Seamless Tubes (t ST); bars - Wire Rod (b WR), Reinforcing Bar (b RB), Hot Rolled Bar (b HRB); shapes - Heavy Section (s HS), Light Section (s LS)) and one of all over 10 end-use sectors (Construction - Buildings (C Bu), Infrastructure (C In); Industrial Equipment - Mechanical Engineering (I ME), Electrical Engineering (I EE); Metal Goods - Other Metal Goods (MG OMG), Appliances (MG Ap), Packaging (MG Pa)). Production & forming scrap (PFS) are calculated via scrap rates for the according process line (e.g. higher share of continuous casting from 1970s on). The sector split for each intermediate product is adapted from Cullen et al., (2012) and calibrated based on EG (1976, 1985, 1990) and Eurofer (2018). The fabrication scrap (FS) is calculated by applying sector and intermediate specific material efficiencies. Post-consumer scrap recovered (PoCSr) is determined by balancing the process “6. Scrap Market”.

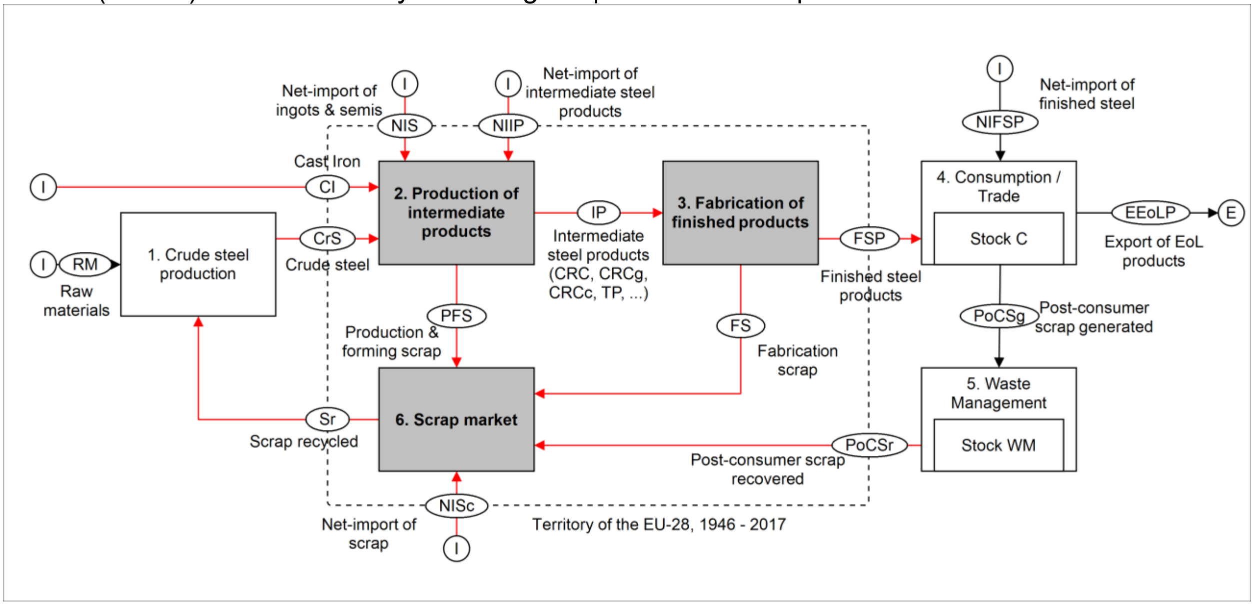

Figure 1: Simplified MFA system for assessing steel scrap flows in the EU-28 (all red steel flows are determined, black flows are just shown completeness); the processes 1., 4. and 5. are located outside of the system boundary and are not considered in this study. Nevertheless, these processes are within the borders of the EU-28, and therefore shown for completeness’s sake.; Stock C ... consumption stock; Stock WM … stock in waste management (e.g., landfills). (Dworak & Fellner, 2021).

2.2 Data sources utilized for steel flows

In the following, the data used is described. For more detailed description the reader is referenced to Dworak & Fellner (2021).

Crude steel production (CrS): The crude steel amount was assessed based on published and reported data from the World Steel Association (1967-2017) and Eurostat (prior to 1967). Where needed, the production data was upscaled for the whole region from available data (e.g., EU-6 to EU-28).

Net-import of semis & ingots (NIS) and intermediate products (NIIP): Trade data from the UN comtrade data base was used to determine net import of the semis and the different steel intermediates since 1994. For the years prior to 1994, only total amounts of imports are available for the EU28 (from 1972 onwards) or the EU6 (prior to 1972) are available. In combination with global trade statistics provided by the World Steel Association (International Iron and Steel Institute, 1978), the net-imports of ingots & semis and steel intermediates were calculated for the according years.

Intermediate products (IP): The domestic production was widely adopted from published data from the World Steel Association (1984-2017). For 2004 to 2017, more detailed data from Eurofer (Eurofer, 2018) was available and was incorporated accordingly in the existing dataset. For earlier years, the Iron & Steel Yearbooks of Eurostat (1970, 1977, 1985, 1994, 1998, 2002) were used, and accordingly upscaled (from EU-6, EU-9, EU-12 and EU-15 to EU-28) when needed.

Net-import of scrap (NISc): The net-imports of scrap was mostly obtained from Eurostat (1955-1970 and 1988-2017). Data for the period 1971-1987 was obtained from the statistical yearbooks provided by the World Steel Association. For the earliest years (1946-1954) the data was extrapolated on basis of available data.

Scrap recycled (SR): Since 1967, the amount of utilized scrap is reported and published by the World Steel Association. Prior to that (1945 to 1966), 50% of the crude steel production was assumed to be based on scrap. The assumption bases on reports of the late 1960s (World Steel Association) and data provided by Eurostat for the EU-6 (Eurostat, 1970).

Transfer coefficients (sector split and material efficiency): Sector splits were derived from different sources (based on Cullen et al. (2012) calibrated using EG (1976, 1985, 1990) and Eurofer (2018)). The material efficiency (loses while fabrication resulting in fabrication scrap) was based on Cullen et al. (2012), whereas the rates were adjusted over time to account for improved material efficiency (improvement for flat products: 15%, for long products: 5%).

2.3 Quality assessment of steel and scrap

The quality was assessed based on the sum of major tramp elements (impurities of Cu, Sn, Cr, Ni and Mo). Four quality classes were considered, based on the level of the considered tramp elements and assigned to steel flows, depended on intermediate and destined end-use sector. In Table 1 the quality categories, according thresholds and typical steel intermediates in the according category. The sector and intermediate specific classification are adopted from Dworak & Fellner (2021).

Table 1: Quality categories based on max. tolerable tramp element content (Dworak & Fellner, 2021)

Max. content of tramp elements	Quality category	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)

2.4 Material Pinch Analysis

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

In this study, we used a per annum material pinch analysis approach, where the available scrap is compared with the crude steel demand, considering the purity of scrap and the requirements of crude steel. Rather than only considering the dilution potential, also the export of lower purity scrap fractions was considered. This approach was chosen, to assess the possible export of surplus scrap of lower purity, which might be the case in open scrap markets (unlimited in- and exports of scrap).

3. RESULTS

The in the following presented results are adopted from Dworak & Fellner (2021).

3.1 Scrap quantities

3.1.1 New scrap (production & forming scrap, fabrication scrap)

Production & forming scrap: Up to the 1970ies, the amount of production & forming scrap increased constantly. From the mid 70ties to the 1990ies, the amount of production & forming scrap decreased dramatically even though the production of crude steel was more or less stable. In this period, the production lines were adapted (continous castig), which led to a tremendous increase of material efficiency during production & forming.

Fabircation scrap: The fabrication scrap increased with the increasing crude steel production, but at a higher rate than curde steel production. This is mainly accountable to the increasing share of flat steel products, which tend to have lower material efficiencies in fabrication. This circumstance also leads to an increasing share of flat products in fabrication scrap (77% in 2017). One of the sectors with high shares of flat steel intermediates is cars. We can see, that about 30% of the fabrication scrap generated originates from this sector, but only 11% of steel in end-use, which underlines the significance of steel intermediate specific material efficiencies. The share of fabrication scrap relative to crude steel production lays at about 17%.

3.1.2 Old scrap (post-consumer scrap)

The post-consumer scrap recovered was calculated by balancing the process “6. Scrap market”. We assumed, that all scrap utilized minus new scrap is the actually recovered post-consumer scrap. The amount of post-consumer scrap recovered increased tremendously (from 5 Mt/yr in 1946 to 74 Mt/yr in 2017, see Figure 2). We can observe an increase of the the relative share of post-consumer scrap from 30% to 70%.

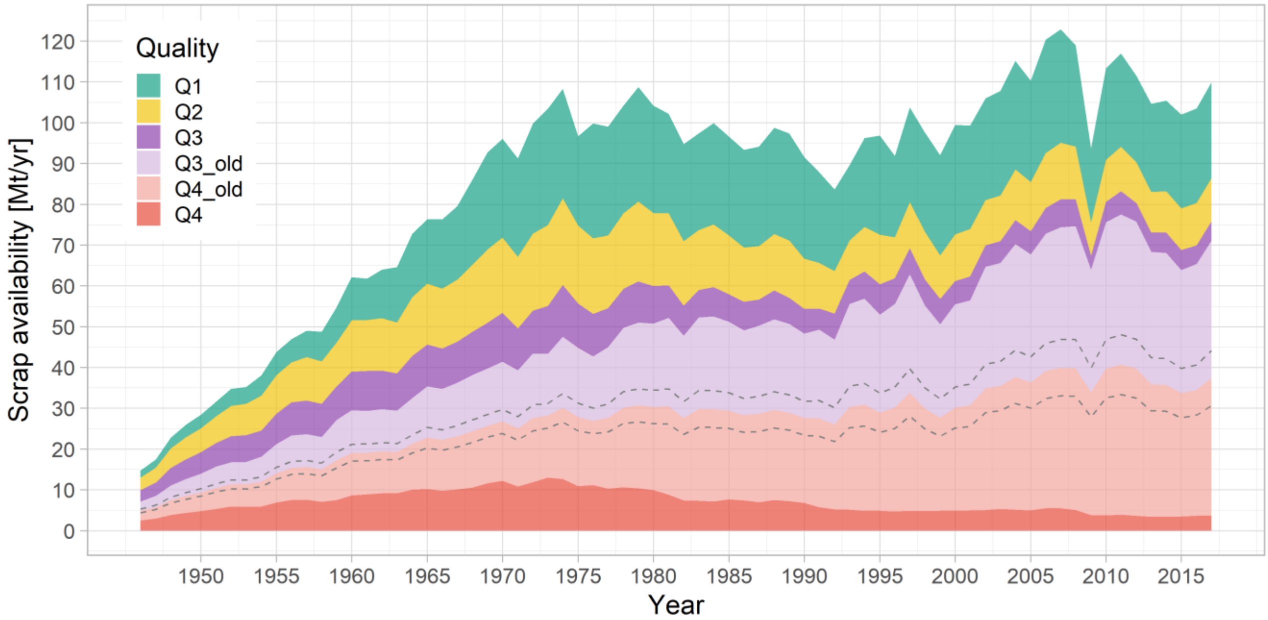

Figure 2: Annual total of new (production & forming, fabrication) and old (post-consumer) scrap generated (given in [Mt/yr]) categorised by quality. The dashed lines visualize the uncertainty of the quality assessment for old (post-consumer) scrap (40% to 60% to Q3 and Q4, each). (Dworak & Fellner, 2021)

3.2 Scrap and steel qualities

New scrap (production & forming scrap, fabrication scrap) is nowadays mainly composed of high purity fractions (55% Q1, 25% Q2), while until the 1960ties, the shares of all four quality categories (Q1, Q2, Q3, Q4) were almost equal. For post-consumer scrap, we assumed that it was composed of 40%-60% each Q3 and Q4. In Figure 2 the overall quantities of scrap available with the according quality categories is shown.

The crude steel demand underwent a shift to a higher amount of high purity fraction (Q1) in the recent decades, while the shares of low purity fractions (Q3, Q4) decreased. This can be attributed to the shift of European steel production from long products to flat products.

In Figure 3 (upper part) snapshots (years 1960, 1980, 1990, 2000, 2010, 2017) of the applied material pinch analysis are displayed. Comparing the crude steel demand and the available scrap with considering the available (scrap) and required (crude steel) purity, we observe that from the early 2000ies on, the amount of available low purity scrap (Q3, Q4) surpluses the crude steel demand in this quality categories (Figure 3, lower part). Comparing this surplus with the reported net-export of post-consumer scrap (HS code 720449), we can see a rather good fit, which indicates, that in practice most of the surplus scrap with low purity is exported rather than diluted and utilized in higher purity crude steel fractions.

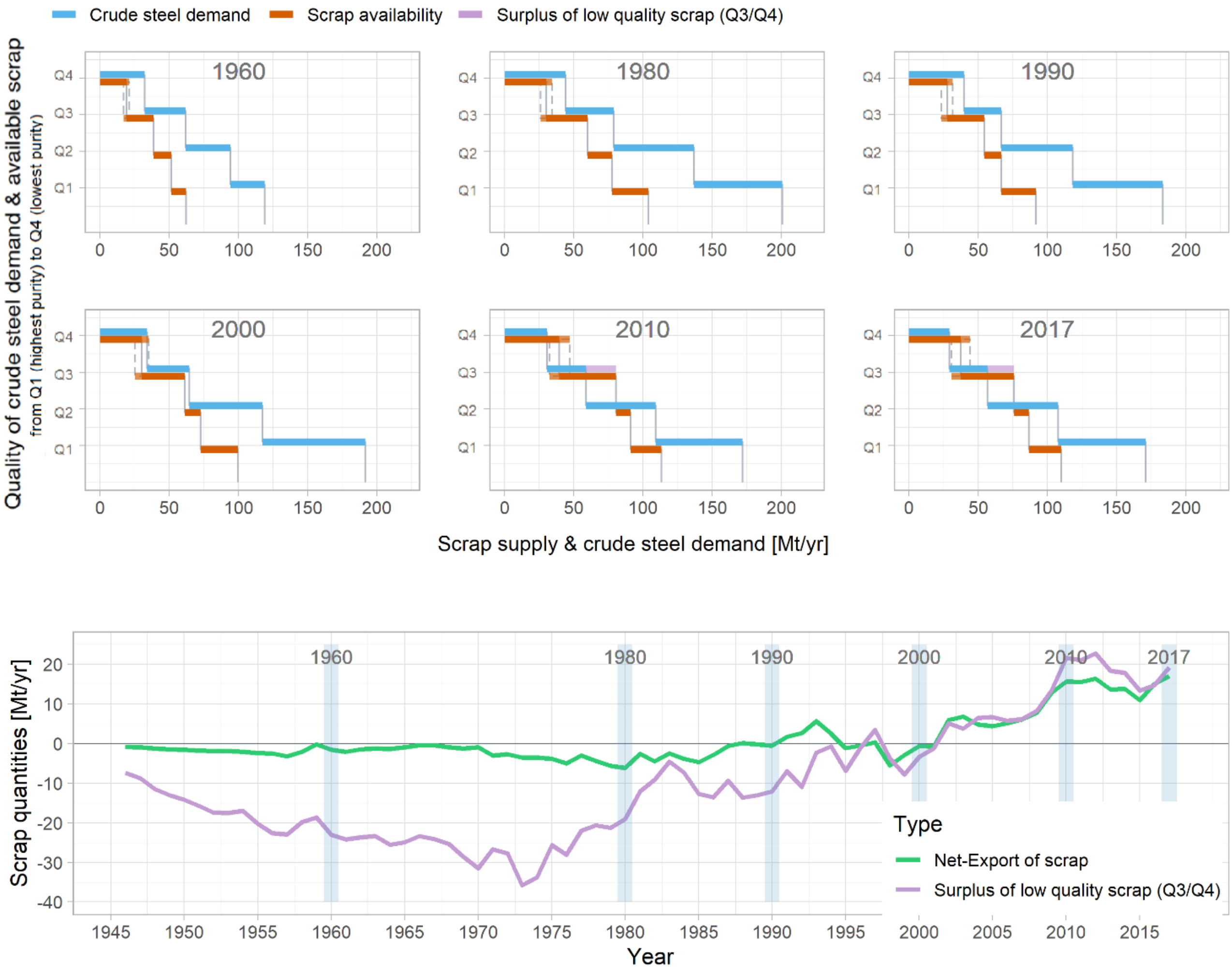

Figure 3: upper part: Material pinch analysis for the quantities and qualities of crude steel demand and available scrap in the EU-28 for the years 1960, 1980, 1990, 2000, 2010 and 2017, The overlap between Q3 & Q4 accounts for the uncertainty of the quality assessment for old (post-consumer) scrap (40% to 60% to Q3 and Q4, each); lower part: Assessed low purity scrap (Q3 & Q4) surplus and net-export of scrap from the EU-28. (Dworak & Fellner, 2021)

4. DISCUSSION AND CONCLUSION

The amount of scrap available not only increased nearly tenfold (14 Mt/yr in 1946 to 120 Mt/yr in 2017) in last 70 years, but also underwent a shift in composition, from dominantly new scrap (80% in the 1950s) to dominantly old scrap (60%). As post-consumer scrap is of rather low purity (Q3, Q4), the share of low purity fractions was increasing in the available scrap. Further, the crude steel demand requires increasing fractions of high purity, due to the shift to higher shares of flat products domestically produced. Hence, if we compare scrap availability with the crude steel demand, also considering quality, a surplus of low purity scrap (Q3, Q4) can be identified. By comparing this surplus with trade data on post-consumer scrap, we can observe a rather good fit between net-exports and the surplus of low purity scrap. This circumstance indicates, that the scrap of low purity is rather exported than diluted and utilized in the domestic steel production. Globally, the steel production is still increasing, while affluent countries/regions like the EU28 or the US did not experience increasing steel production volumes for some decades now (World Steel Association, 2020). We can assume, that at some point, the demand for low purity scrap will ebb away, as these countries will also reach a saturation level, where the domestic scrap, potentially low purity scrap, needs handling. Therefore, to be able to utilize as much scrap as possible in crude steel production, a different handling of old scrap is necessary. Daehn et al. (2019) argue, that alloy sorting is mandatory for more efficient handling of post-consumer scrap. Further, several technical interventions might be considered. For one, undesired tramp elements might be removed from the melt (e.g., vacuum distillation, sulphide slagging) or re-design of processes (e.g., direct strip casting (Spitzer et al., 2003)) and materials (e.g., adding interaction alloys for contra balance unfavourable properties) allow higher tramp element contents (Daigo et al., 2021).

ACKNOWLEDGEMENTS

The work presented is part of a large-scale research initiative on anthropogenic resources (Christian Doppler Laboratory for Anthropogenic Resources). The financial support of this research initiative by the Federal Ministry of Digital and Economic Affairs and the National Foundation for Research, Technology and Development is gratefully acknowledged. Industry partners co-financing the research centre on anthropogenic resources are voestalpine AG, Altstoff Recycling Austria AG (ARA), Borealis group, Wien Energie GmbH, Wiener Kommunal-Umweltschutzprojektgesellschaft GmbH (WKU), and Wiener Linien GmbH & Co KG. In addition, the authors would like to thank Christian Brandstätter and Manuel Hahn (both TU Wien) for their support in data research (e.g. UN Comtrade data base and vehicle statistics). In addition, the data support of Adam Szewczyk (World Steel Association), Freddy Caufriez (Eurofer) and Nina Kieberger (voestalpine AG) is gratefully acknowledged.

REFERENCES

Broadbent, C. (2016). Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy. *International Journal of Life Cycle Assessment*, *21*(11). https://doi.org/10.1007/s11367-016-1081-1

Brunner, P. H., & Rechberger, H. (2016). *Handbook of Material Flow Analysis for Enviromental, Resource, and Waste Engineers* (2nd ed.). CRC Press - Taylor & Francis Group.

Cooper, D. R., Ryan, N. A., Syndergaard, K., & Zhu, Y. (2020). The potential for material circularity and independence in the U.S. steel sector. *Journal of Industrial Ecology*, *24*(4). https://doi.org/10.1111/jiec.12971

Cullen, J. M., Allwood, J. M., & Bambach, M. D. (2012). Mapping the Global Flow of Steel : From Steelmaking to End-Use Goods. *Environmental Science and Technology*, *46*(24). https://doi.org/10.1021/es302433p

Daehn, K. E., Cabrera Serrenho, A., & Allwood, J. M. (2017). How Will Copper Contamination Constrain Future Global Steel Recycling? *Environmental Science and Technology*, *51*(11). https://doi.org/10.1021/acs.est.7b00997

Daehn, K. E., Serrenho, A. C., & Allwood, J. (2019). Finding the Most Efficient Way to Remove Residual Copper from Steel Scrap. *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science*, *50*(3). https://doi.org/10.1007/s11663-019-01537-9

Daigo, I., Tajima, K., Hayashi, H., Panasiuk, D., Takeyama, K., Ono, H., Kobayashi, Y., Nakajima, K., & Hoshino, T. (2021). Potential influences of impurities on properties of recycled carbon steel. *ISIJ International*, *61*(1), 498–505. https://doi.org/10.2355/isijinternational.ISIJINT-2020-377

Dworak, S., & Fellner, J. (2021). Steel Scrap Generation in the EU-28 since 1946 – Sources and Composition. *Resources, Conservation and Recycling*.

EG. (1976). *Allgemeine Ziele Stahl 1980 - 1985 (General goal for steel: 1980 - 1985). Amtsblatt der Europäischen Gemeinschaften(19/No. C 232)*.

EG. (1985). *Allgemeine Ziele Stahl 1990 (General goals for steel 1990). Amtsblatt der Europäischen Gemeinschaften(K0MC85) 208 endg)*.

EG. (1990). *Allgemeine Ziele Stahl 1995 (General goals for steel 1995). Amtsblatt der Europäischen Gemeinschaften(KOM (90) 201 endg.)*.

Ekvall, T., Fråne, A., Hallgren, F., & Holmgren, K. (2014). Material pinch analysis: A pilot study on global steel flows. *Metallurgical Research and Technology*, *111*(6). https://doi.org/10.1051/metal/2014043

Eurofer. (2018). *European Steel in Figures 2018 - covering 2008-2017*.

Eurostat. (1970). *Iron and Steel - Statistical Yearbook 1970*.

Hatayama, H., Daigo, I., Matsuno, Y., & Adachi, Y. (2009). Assessment of the recycling potential of aluminum in Japan, the United States, Europe and China. *Materials Transactions*, *50*(3). https://doi.org/10.2320/matertrans.MRA2008337

Hatayama, H., Daigo, I., Matsuno, Y., & Adachi, Y. (2010). Outlook of the world steel cycle based on the stock and flow dynamics. *Environmental Science and Technology*, *44*(16). https://doi.org/10.1021/es100044n

Hatayama, H., Daigo, I., Matsuno, Y., & Adachi, Y. (2012). Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology. *Resources, Conservation and Recycling*, *66*. https://doi.org/10.1016/j.resconrec.2012.06.006

Hu, J. Y., Gao, F., Wang, Z. H., & Gong, X. Z. (2014). Life cycle assessment of steel production. *Materials Science Forum*, *787*. https://doi.org/10.4028/www.scientific.net/MSF.787.102

Igarashi, Y., Daigo, I., Matsuno, Y., & Adachi, Y. (2007). Estimation of the change in quality of domestic steel production affected by steel scrap exports. *ISIJ International*, *47*(5). https://doi.org/10.2355/isijinternational.47.753

International Iron and Steel Institute. (1978). *A Handbook of World Steel Statistics*.

Linnhoff, B., & Hindmarsh, E. (1983). The pinch design method for heat exchanger networks. *Chemical Engineering Science*, *38*(5). https://doi.org/10.1016/0009-2509(83)80185-7

López, C., Pea, C., & Muoz, E. (2020). Impact of the Secondary Steel Circular Economy Model on Resource Use and the Environmental Impact of Steel Production in Chile. *IOP Conference Series: Earth and Environmental Science*, *503*(1). https://doi.org/10.1088/1755-1315/503/1/012024

Müller, D. B., Wang, T., & Duval, B. (2011). Patterns of iron use in societal evolution. *Environmental Science and Technology*, *45*(1). https://doi.org/10.1021/es102273t

Noro, K., Takeuchi, M., & Mizukami, Y. (1997). Necessity of scrap reclamation technologies and present conditions of technical development. *ISIJ International*, *37*(3). https://doi.org/10.2355/isijinternational.37.198

Pauliuk, S., Milford, R. L., Müller, D. B., & Allwood, J. M. (2013). The steel scrap age. *Environmental Science and Technology*, *47*(7). https://doi.org/10.1021/es303149z

Pauliuk, S., Wang, T., & Müller, D. B. (2013). Steel all over the world: Estimating in-use stocks of iron for 200 countries. *Resources, Conservation and Recycling*, *71*. https://doi.org/10.1016/j.resconrec.2012.11.008

Sampson, E., & Sridhar, S. (2013). Effect of silicon on hot shortness in Fe-Cu-Ni-Sn-Si alloys during isothermal oxidation in air. *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science*, *44*(5). https://doi.org/10.1007/s11663-013-9876-y

Savov, L., Volkova, E., & Janke, D. (2003). Copper and tin in steel scrap recycling. *Materials Geoenvironment*, *50*(3).

Spitzer, K.-H., Rüppel, F., Viščorová, R., Scholz, R., Kroos, J., & Flaxa, V. (2003). Direct Strip Casting (DSC) - an Option for the Production of New Steel Grades. *Steel Research International*, *74*(11–12), 724–731. https://doi.org/https://doi.org/10.1002/srin.200300256

World Steel Association. (2020). Steel Statistical Yearbook 2020. In *Steel Statistical Yearbook 2020*.

Zhu, Y., Syndergaard, K., & Cooper, D. R. (2019). Mapping the annual flow of steel in the United States. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.9b01016

