Closing the loop: Quality and quantity of scrap in future European steel production.

Quantifying the scrap quality in the circular future of Europe, from an industrial ecology perspective

Master Industrial ecology thesis research project

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28 February 2025

Abstract

The steel industry is undergoing a transition that is driven by two key factors: the decarbonisation of the production process and the promotion of circularity. This transition involves a shift from coal to renewable energy sources for decarbonisation purposes and from iron ore to scrap-based steelmaking, thereby facilitating the transition to a circular economy. In this context, the availability and quality of steel scrap become critical factors in facilitating the transition to scrap-based steelmaking. This master thesis employed a dynamic material flow analysis (dMFA) to assess steel and scrap metabolism in Europe, focusing on trade impacts, scrap sorting, and steel production methods. Three scenarios, no trade deficit(1), business-as-usual trade (2), and high trade deficit (3) were analysed, alongside improved scrap sorting strategies. Key findings indicate that a circular steel industry requires a shift to electric arc furnace (EAF) steelmaking with minimal trade deficits to ensure high-quality scrap availability. Achieving an 80% intermediate level sorting rate for end-of-life steel scrap by 2050 is critical for closing the loop on steel production. Additionally, optimizing scrap distribution within Europe is essential to prevent downcycling and reduce tramp element accumulation. The study underscores the need for Europe to support global sustainable steel production as part of climate responsibility. Future research should refine key assumptions, conduct sensitivity analyses, and enhance scrap categorization and sorting data.

The model, code, and data are available in the supplementary materials.

Table of contents

1. Introduction and research gap

1.1 Research area

The future of European steel production is based on two elements: energy source and feedstocks (Raabe, 2023; Raabe, Jovicevic-klug, et al., 2024a). In accordance with the industry's sustainable development goals, there is a shift from coal to renewable energy sources for decarbonisation and from iron ore-based steelmaking to scrap-based steelmaking to increase circularity. The motivation for this transition is attributable to several factors, including the costs of operational carbon emissions (ETS), demand for circular products by society and the security and independency of feedstocks in future operations.

In the context of this transition, it is important to understand the long-term demand, supply, and environmental impacts in order to formulate a comprehensive coordinated strategy for a net zero emission future for the industry (Watari et al., 2021). This study aims to develop a understanding of the relationship between demand and supply of steel scrap in a circular steel industry. The study will focus on the analysis of steel scrap availability and demand, taking into account the technological constraints of production and the impact of trade with regions outside the European Union. The strategic development of the European steel industry is dependent upon its position within the global steel industry, a position characterized by its capacity for innovation in pursuit of its objectives while maintaining competitiveness on global scale.

The European steel industry is, at the time of writing, experiencing significant challenges, stemming from competition from abroad and the implementation of ambitious environmental policies by the EU and its member states (Bloomberg, 2024; Vögele et al., 2020). In contrast, major economic entities such as China and the United States have utilised a range of protective and subsidised measures to support their steel industries (Raabe, Jovicevic-Klug, et al., 2024b; Vögele et al., 2020). These countries, however, have been accused of distorting fair competition through the practice of steel dumping in the European market (Raabe, Jovicevic-Klug, et al., 2024b; Vögele et al., 2020). The European Union is currently engaged in a debate concerning the introduction of import tariffs as a means of balancing the current trade balance. However, the efficacy of such measures in achieving a complete equilibrium is subject to debate (Vögele et al., 2020). The EU's status as an import economy for steel is underscored by its trade dynamics, evidenced by the export of 16.6 million tonnes (Mt) of finished steel products and the import of 28.9 Mt in 2023. This indicates a partial reliance on imports, predominantly in the sectors of mechanical and electrical engineering, and transport (including cars and trucks), totalling approximately 9 Mt (Dworak et al., 2022). With this trade deficit growing (EUROFER, 2024) in the last decade the steel industry is challenged by economic limitations in innovation for the sustainability transition. Resulting in delays and cancelations of the green steel transition plans (Reuters, 2024b, 2024a, 2025).

1.2 Steel production

The global production of steel is predominantly categorised into two distinct processes: the blast furnace with basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF). With EAF the steel can be produced from steel scrap or direct reduced iron (DRI), this is a way of removing the oxygen from iron ore with hydrogen and carbon monoxide, typically coming from natural gas, coal or coal gas. The BF-BOF is the main way to produce primary steel with coal and iron ore. The aggregate global production of steel is approximately 2 billion ton annually, with 71.1% of this production occurring via the BF-BOF route and 28.6% via the EAF route (Word Steel, 2024). The associated emissions average at 2.33 tonnes of CO_2 per tonne of crude steel for BF-BOF compared with 1.37 tonnes of CO_2 per tonne of crude steel produced with DRI, or 0.68 tonnes of CO_2 per tonne of crude steel produced with scrap, strongly depended on the energy source (of hydrogen) (Word Steel, 2024). In Europe, the production of 126 Mt crude steel is distributed as follows: 55% is produced with the BF-BOF and 45% with EAF (EUROFER, 2024).

Concerns regarding the environment, in combination with the subsequent implementation of relevant policies, have initiated a transition from fossil-based energy sources such as coal and natural gas in the primary steel production sector towards the use of renewable energy sources, with a focus on hydrogen. (Raabe, Jovicevic-klug, et al., 2024b; Watari & McLellan, 2024). Concurrently, enhancing material efficiency and augmenting the utilization of steel scrap can curb the environmental impact of the steel industry (Raabe, Jovicevic-klug, et al., 2024b). The steelmaking with higher levels of steel scrap has been demonstrated to reduce the environmental emissions, as wel as decrease in the energy required to produce steel from iron ore (Voraberger et al., 2022)). With EAF it is possible to produce steel from 100% scrap (Nuñez et al., 2024). Contrary to this, the utilization of scrap in the BF-BOF process is more complex due to the energy balances involved in the process. Typically, scrap is introduced into the converter after the production of liquid iron in the blast furnace. For a more comprehensive overview of the steel production process, please refer to the supplementary materials A, which include a detailed flow diagram.

The process of scrap melting is a highly energy-intensive process within the context of liquid iron production. In instances where the addition of scrap exceeds the limit, the steel can solidify within the ladle. This is detrimental in the production process cause many costly problems. Empirical evidence suggests that the maximal range for scrap input typically falls within the 20 to 30% range of scrap input, contingent upon the specific characteristics of the blast furnace facility in question (Voraberger et al., 2022). It is acknowledged that there are technologies available for increasing the scrap input to a maximum of 50%, yet these necessitate the implementation of additional technologies (Voraberger et al., 2022). One such example is the addition of energy to facilitate the melting of the scrap, although it should be noted that this also results in increased costs and environmental impacts.

The transition to more scrap-based steelmaking thus reduces upstream emissions of the iron and coal for mining and processing (Ferreira & Leite, 2015; Tao et al., 2022). Also, reducing the use of coal and iron could stabilise the cost of steelmaking over time as described in Vögele et al (2020). This research highlights that the historical price of iron ore and coal is volatile. The price of coal increased 600% from 2000 to 2008 and after 2008 a 70% drop with a following increase again. The prediction of these prices in the future is a difficult task as it is depended on a complex system, but less dependency on iron ore and coal can be argued to be a positive influence for the stability of costs of steel production. However, the big question for the shift to scrap-based steelmaking is whether there is enough scrap to meet demand. The relative amount of scrap in Europe is one of the highest compared to other regions, Pauliuk et al. (2013) estimate that in 2050 Western Europe will have a balance on the amount of scrap available as the steel demand. The balance in Western Europe is reached due to two factors, firstly the increasing outflow of scrap from the stock, caused by the end of life of historic build up stocks. Secondly, the projected decrease of demand due to saturation. But this mass balance approach ignores the impact of the quality of steel and scrap.

1.3 Steel scrap quality challenges

The steel in use by society is comprised of numerous alloys and chemical compositions, and the steel scrap returned from use, fabrication and production is likewise constituted of these alloys and thus also contains a multitude of chemical compositions (Raabe, Jovičević-Klug, et al., 2024). Contamination from coatings, processes, connected components or particles from the scrap origin product life can also be a factor. The unwanted or tramp elements present in the scrap can have a detrimental effect on the properties of the steel, including mechanical and surface finishes (see supplementary material B for a comprehensive overview table detailing elements, typical origins, effects and removal options).

The primary indicator of the quality of steel scrap is defined by the presence of the five most critical tramp elements (Cu, Sn, Ni, Mo, Cr). These elements are particularly challenging to extract from the liquid phase through conventional steel-making processes. The conventional method for removing these elements involves the introduction of oxygen into the steel bath during the converter process, where tramp elements (alongside carbon, which is integral to the steel-making process) are removed from the liquid steel and deposited as slag (Papamantellou et al., 2024.; Raabe, Jovičević-Klug, et al., 2024; Sommerfeld et al., 2024). A significant challenge in this process is the difficulty in removing these "big 5" elements, which are more resistant to removal than iron. This is illustrated in the Ellingham diagram (Hasegawa, 2014), which shows the ease of oxidation of these elements. This situation gives rise to an accumulation of tramp elements in steel qualities, with related quality challenges. These challenges will increase when industry changes to more scrap-based steelmaking (Daehn et al., 2017).

The most cost-effective and accessible technological approach to address the tramp elements in scrap is mechanical sorting prior to smelting. A substantial body of research has been conducted in academia and industry on sorting and separation techniques (Boom & Steffen, 2001; Gao et al., 2021; Ohno et al., 2017a; Quintè, 2023; Tata Steel Europe, 2025). There is an increasing number of companies specialising in sorting techniques. Concurrently, steel industry actors and scrap suppliers are engaged in the development and patenting of novel technologies. However, the research that exists that provides a comprehensive overview of the current state of sorting in Europe is scarce to non-existent.

An alternative approach to address the impurities in steel is to adapt the manufacturing processes and alloy composition to achieve the desired properties of the steel (Raabe, Jovičević-Klug, et al., 2024). One such approach involves the addition of nickel, which has been shown to mitigate the impact of copper. Alternatively, the processes of casting and rolling mills can be adapted to affect the microstructure and have the same quality of steel with higher tramp elements, although this can become challenging due to the many factors affected by such changes.

The processing and innovation required to address the substantial quantity and diverse quality of scrap, in order to meet the demands of the steel industry, represents a complex transition. This process necessitates the mobilisation of all available knowledge and expertise to minimise the environmental impact to the greatest extent possible.

1.4 Responsibility

The argument can be made that the steel industry should take on more responsibility than merely sustainability directly related to production, and that this responsibility extends to the development of more efficient steel use. This assertion is based on the premise that steel production will always be an environmental impact and energy-consuming process, even in scenarios where all steel is produced using renewable energy sources and scrap. To achieve a zero-emissions future, as aspired to by the global community (Watari, Hata, et al., 2023), a reduction in production would be necessary. However, a challenge would be to design a world where steel is used as efficiently as possible while maintaining a high living standard. Steel is currently a major factor in all essential processes, e.g. food, healthcare, education, transportation, for this living standard (Cullen et al., 2012). However, reducing the production and promoting more efficient use would be at odds with the current profit models of the steel industry, where the profit margin on steel is minimal and costs are high, necessitating the production of large quantities of steel to generate profit. The future of scrap-based steelmaking has the potential to reduce costs and create space for systemic change (Ohno et al., 2017a; Watari, Giurco, et al., 2023a). In addition, alternative business models may need to be explored, such as product as a service (Krummeck et al., 2022), where steel is not sold directly but leased, thereby creating an incentive to optimize products for recycling.

As Watari et al. (2023) demonstrate in their paper, the zero-emission future of the world is also under pressure from another perspective. By 2050, the quantity of steel scrap in Global North countries will equal their demand. This is not the case for most regions in Global South, where the available scrap would not be sufficient to fulfil demand. This would result in the Global North producing inexpensive and environmentally friendly steel, while the Global South still be producing primary steel from iron ore and coal. Consequently, the Global South would face challenges in producing steel in a sustainable manner to meet its basic living standards, exacerbating the already existing disparity in steel production and environmental impact between the Global North and South.

1.5 European research on scrap quantity quality

The existing body of research on the quantification of scrap flows in Europe is limited in terms of studies that have attempted to quantify the European steel metabolism. A review of the literature reveals three studies that have employed material analysis to quantify the steel cycle (Dworak et al., 2022; Panasiuk, 2022; Rostek et al., 2022). Of these, Panasiuk et al. (2022) and Rostek et al. (2022) adopt a retrospective approach, whilst Dworak et al. (2022) proffers a forward-looking perspective, building upon a previous retrospective study by (Dworak & Fellner, 2021a).

The Dworak and Fellner (2021a) focus on steel flows in Europe from 1947 to 2017, using trade data and material intensity of products to describe the system, with a focus on intermediate production, fabrication, and the scrap market. In the subsequent paper (Dworak et al., 2022), the scope of research is expanded to encompass consumption and waste management, with the temporal frame widened to 2017-2050. This provides insights into the flows and quality demands of scrap in various scenarios. Dworak et al. (2022) present three scenarios, with Option A assessing the quality of scrap at the sector level, Option C at the intermediate level, and Option B as somewhere in the middle between a and C. The interpretation of these scenarios indicates that Option A involves the scrap from individual sectors that are not subjected to further analysis for composition, but rather assigned to a quality class, representing the worst-case scenario for closed-loop recycling. Option B involves the mixing of all scrap from individual sectors with the average tramp elements to determine the quality class. Option C entails the separation and recycling of every intermediate separately, representing the best-case scenario for closed-loop recycling. The outcomes of these approaches align with the anticipated results, with Option C yielding a higher proportion of high-quality scrap, Option B producing a median outcome, and Option A yielding the lowest yield. Panasiuk's (2022) study

employs the same methods for an MFA, with an estimation of the iron content in the stocks and flows in Europe, focusing on losses. The study describes the result of 65% of the end-of-life steel scrap being recycled in Europe, with the rest being lost in obsolete stocks and losses.
In the context of the MFA on steel flows at a global scale, a study by Deahn et al. (2017) offers a comprehensive overview of global steel flows, with a particular emphasis on the presence of copper contamination and accumulation. The analysis reveals that a significant proportion of scrap is allocated to EAF steelmaking for lower qualities, underscoring the current system's limitations in terms of a holistic, circular future for the industry as a whole. The study by Pauliuk et al. (2013) provides a comprehensive overview of the steel system modelled with a MFA, along with an estimation of the available scrap and a projection of when it will meet global demand. The study forecasts that by 2050 the quantity, without discussing the quality, of scrap will be sufficient to meet the demand in Western Europe, and by 2100, the global supply is expected to be equal with the availability of scrap. The estimation is based on a comprehensive description of the saturation of scrap in different world regions, with a notable plateau in developing nations around the year 2050 and a subsequent plateau in developing regions.

1.6 Research questions

The existing literature does not address the impact of trade in steel and scrap between developed regions and the rest of the world on this supply-demand nexus. Furthermore, the current analysis is based on a mass comparison of supply and demand. It does not consider the production technologies available for the actual use of scrap in steel production. This research aims to fill this research gap, subsequently the following research questions are developed.

How does steel trade and the steel production methods, impact scrap-based steelmaking within Europe, considering the quantity and quality of steel and scrap, in the period of 1911 to 2100?

Nr	***Sub research questions***	***Methods***	***Data sources***
1	What methodology can be used for modelling steel and scrap metabolism for the EU from 1911 to 2100?	Literature and expert research	Literature, experts on steelmaking, modelling and scrap
2	What is the impact of the European production methods on the scrap metabolism?	python modelling dMFA of production process	Literature, experts on steelmaking, modelling and scrap
3	What is the impact of finished steel products and intermediates import on the steel scrap metabolism?	python modelling dMFA of import scenario's	Literature, experts on steelmaking, modelling and scrap
4	What is the effect of the innovation of scrap sorting technologies and practices on the steel scrap metabolism?	Literature and expert research and python modelling dMFA	Literature, experts on steelmaking, modelling and scrap

2. Data and Methods

2.1 General approach

The quantity and quality of steel flows are assessed by means of a dynamic Material Flow Analysis (dMFA) method. The MFA methodology is adapted from the Handbook of MFA (Brunner & Rechberger, 2016). The steps for this type of modelling are defined as follows: first, the system is defined; then, data is collected; next, the modelling is conducted; and finally, the model results are analysed.

The dynamic MFA method is adapted from several papers and methodological reviews (Dworak et al, 2022b; Müller et al, 2014; Panasiuk, 2022; Pauliuk et al, 2013b). In particular, Müller et al. (2014) describe the research methods for extrapolating the data into the future. This extrapolation of the data is described in paragraph 3.5 Model parameters.
The overarching objective of the model is to map the steel scrap metabolism in the European Union from 1911 to 2050. The research of Dworak et al. (2022) provides a system for modelling the steel industry. This research is building on this system by expanding the system boundary to include production and scrap market (see Figure 3.1) and modelling three scenarios on trade deficit of steel and steel products. Another improvement on the existing literature is the addition of a scrap sorting parameter that increases over time (subparagraph 3.5.6).

Table 3.1. *Overview of intermediates and sectors*

nr	*Intermediates*	*Sectors:*
1	Hot Rolled Bar (HRB)	Construction Buildings (C Bu)
2	Reinforcing Bar (RB)	Construction In Infrastructure (C In)
3	Wire Rod (WR)	Electrical Engineering (I EE)
4	Cast Iron (CI)	Mechanical Engineering (I ME)
5	Cast steel (CS)	Other Metal Goods (MG OMG)
6	Cold Rolled Coil (CRC)	Cars (T Ca)
7	Cold Rolled Coil coated (CRCc)	Other Transport (T OT)
8	Cold Rolled Coil galvanized (CRCg)	Trucks (T Tr)
9	Electrical Strip (ES)	Appliances (MG Ap)
10	Hot Rolled Coil (HRC)	Packaging (MG Pa)
11	Hot Rolled Coil galvanized (HRg)	
12	Hot Rolled Narrow Strip (HRNS)	
13	Plate (P)	
14	Tin Plated (TP)	
15	Heavy Section (HS)	
16	Light Section (LS)	
17	Rail Section (RS)	
18	Seamless Tubes (ST)	
19	Welded Tubes (WT)	

The model used is a demand driven method where demand is specified in sectors and intermediates. Table 3.1 shows the 10 sectors and 19 intermediates. The model specifies which intermediate is used in which sector, resulting in 100 unique combinations of sector and intermediate. These combinations are then further modelled with specific parameters per sector, intermediate or sector-intermediate combination.

2.2 Definition of the system and flows

The system boundaries have been adapted from Dworak et al (2022). The system boundary has been extended to encompass the system, the seventh scrap market, and the first crude steel production. The system under consideration comprises a total of seven processes, with 15 flows and two stocks. Logically beginning with process 1 as the point of steel entering the techno-cycle of scrap.

Process 1: Steel and hot metal (used for cast iron intermediates and products) are produced from raw materials and scrap. The specification of the production of different grades of steel intermediates and semi's is further explained in paragraph 3.5.6. For process 1 it is important to note that the flow of raw materials entering process 1, called "crude steel production", is not quantified in the model as it is outside the scope of the study, but is visualized in the diagram for completeness.

Process 2: In Process 2, the intermediate steel products and semi-finished products from Process 1 are mixed with imports and exports to and from outside the EU. In this process, the semi-finished products are processed into intermediate steel products, which are sent to process 3. In this process, production and forming scrap is released to the scrap market, which is further specified in paragraph 3.5.3.

Process 3: The intermediate steel products from process 2 are processed into finished steel products that go into process 4. The fabrication of finished steel products generates fabrication scrap, which enters the scrap market.

Process 4: The finished steel products in process 4 can be mixed and exchanged with imports and exports to and from outside the EU. It is assumed that a product produced in the EU and a product imported from the EU are interchangeable. For example, a car produced in Germany is assumed to have the same quantity and quality of steel as a car produced in Japan. This assumption is made for all sectors, resulting in a net import figure. It does not take into account any scrap that may be lost in the process, for example during transport.

Process 5: In the consumption process, finished steel products enter. These finished steel products are not specific in the model flows, but are divided into sector-intermediate combinations. So, for example, for all finished transport equipment consumed in year x, the sum of all intermediates is the steel consumption. For the cars and trucks leaving the system, an end-of-life (EOL) product export flow is modelled (further specified in section 3.5.2). There is a stock for the steel in use and after use, when the lifetime of a product is over, there is a steel that is released as EOL scrap.

Process 6: The EOL scrap from process 5 is treated in process 6. waste management. Not all this scrap is recovered, and this varies from sector to sector (see section 3.5.2 for more details). From this process there is a flow of recovered post-consumer scrap going into the scrap market.

Process 7: In the scrap market, production, manufacturing and post-consumer scrap is categorized and sorted. Sorting can take place at sectoral, intermediate or sectoral-intermediate level (further specified in paragraphs 3.5.5 and 3.5.6). The scrap market is a crucial component in maintaining the mass balance of the system, assuming that steel scrap not used for steelmaking is exported to regions outside the European Union. It is also assumed that there are no stocks in the scrap market, i.e. scrap is not stored for more than one year. It is recognized that certain scrap suppliers have the capacity to store their scrap for more than one year in order to secure more favorable prices. However, this aspect has not been included in the model outlined. From this scrap market, the scrap that is recycled is used in crude steel production to create a full cycle.

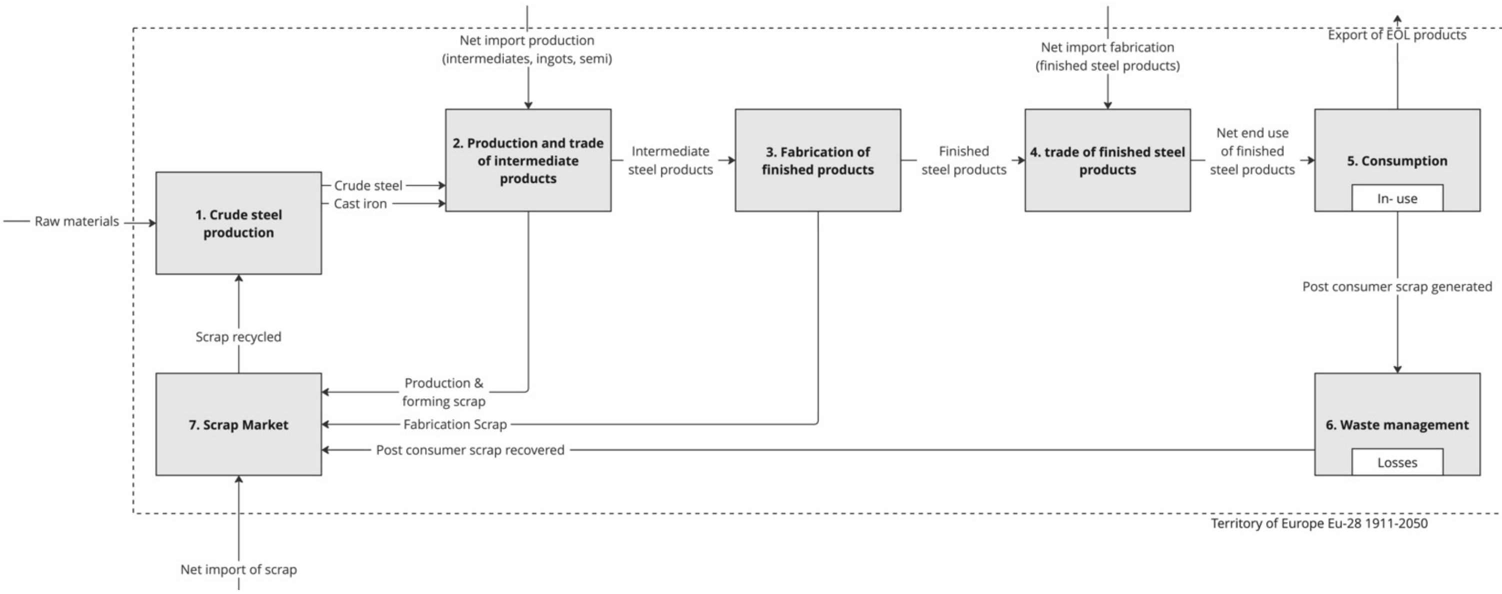


Fig. 3.2. *System description for the dynamic material flow analysis*

2.3 Data collection

Demand for finished steel products can be estimated with international trade data and company reports. Trade in finished steel products can be converted into mass flows, if necessary, using material intensity data. The underlying dataset for this study is based on Dworak et al. (2022). This research analysed trade data and created a dataset for Europe (EU28) from 1911 to 2018. In this research, European stocks and flows are analysed in a dMFA and the results are validated with top and bottom-up approaches for buildings and cars. The 2022 study builds on a previous study by Dworak and Felner (2021), which covers the period from 1950 to 2019. For more details on the construction of this dataset, see Dworak et al. 2022. There is assumed that the stock of steel in society in 1910 is zero, as there is no good stock data estimation available of that time. This is argued to give a lower scrap generation in the 20th century. With the timeframe and thus the minimal effect on the results of this study in mind it is not further researched or improved.

The base dataset provides a quantity of scrap and steel demand for each sector-intermediate combination for each year up to 2018. This is used as the demand for finished steel products. From 2018 to 2100 this demand will be fixed at the 2018 value. This is an assumption made as demand is not within the scope of the research. There are several estimates describing the growth, stabilization or decline in demand for steel products. Pauliuk et al. (2013b) describe the peak of European demand in 2022 at around 175 Mt per year and then a decline to a stabilization point at around 100 Mt per year in 2100. The same trend is described by other sources, but with a different time for the peak (between 2020 and 2035) and the stabilization year (between 2040 and 2100). A different stabilization value is also described, between 100 and 200 Mt per year and a peak between 200 and 300 Mt per year. (Bataille et al., 2018; IEA, 2023; Watari, Giurco, et al., 2023b; Watari, Hata, et al., 2023). Our dataset gives a demand of around 120 Mtpa in 2017, which is well within the range of the other scenarios and is so adopted for this research.

Paragraph 3.4 describes the parameters and data for the scenarios and paragraph 3.5 describes the data and parameters for the other model parameters.

2.4 Trade scenario's

The importation of steel intermediates, ingots or semi-products ('production import') or finished steel products ('FSP import') is directly linked to reduced consumption of scrap and lower availability of production and fabrication scrap. Firstly, the consumption of scrap is caused by the reduced utilization of scrap in domestic steel production. Secondly, the reduced availability of scrap is attributed to diminished production and fabrication, leading to a concomitant decrease in scrap generated during these processes (see Paragraphs 3.5.3 and 3.5.4 for details). This dynamic provides a dynamic that can defined in three scenarios involving varied values of the trade balance on steel containing products. This trade balance is defined as import minus export for all steel intermediates used in every sector.

In this research three distinct scenarios are used:

Trade scenario 1: Trade balance, This scenario is modelled to demonstrate the balance between the exports and imports of finished steel products and intermediates of the EU. The scenario depicts a future characterized by a balanced trade in goods and intermediary products, e.g. a balance in the number of cars exported and imported.

Trade scenario 2: Business as usual, The business-as-usual scenario is modelled as an average of the 2010-2018 trade balance data (Dworak et al, 2022, Eurofer, 2024). The selection of this time period was motivated by the perception of a relatively stable economic climate during this interval. The mean trade deficit value of FSP to the total FSP flow is calculated to be 1%. The production trade deficit is calculated to be 0.5%, describing the total import of products to the total demand of intermediate steel products. The highest values recorded during this period were 3.1% for relative trade deficit in relation to fabrication and 1.9% for production. Conversely, the lowest values are observed in the production sector, with a relative trade deficiof 0.2% and a relative export of 0.2%. It is important to note that the historic import and export values exhibit significant fluctuations over time, sometimes reaching over 15Mt in export and 20Mt in import for production. For fabrication, the range is from 8 to 0 Mt import over the past 50 years. This results in an average fabrication trade deficit value of 1.6% and a production trade deficit value of 5.2% in this time period.

Trade scenario 3: High trade deficit, this scenario has 50% added to the relative trade deficit of scenario 2. Resulting in 51% for fabrication and 50,5% for production. Describing an extreme scenario's, to enlarge the effect for analysis.

When there is a change in the import percentages, there is a corresponding change in the domestic fabrication and production values. The results of this relationship are illustrated in the supplementary material C.

2.5 Model parameters

The following parameters are individually discussed: lifetime, recovered and exported end-of-life-scrap, production scrap, fabrication scrap, quality of steel intermediates, quality of scrap and production matrix.

2.5.1 Lifetime

The lifetime of a product in society is defined as the time that it is in use, and at the end of its lifetime, the product's steel is released as end-of-life scrap. The lifetime for the different sectors is adapted from Dworak et al. (2022), where the lifetime is defined for every sector. This dataset is compiled of more than 12 papers, describing the products in sector. The full list of mean lifetimes can be found in the supplementary material , with a range of 65 years for building and infrastructure and a year for packaging. The lifetime distribution is modelled using a Weibull distribution curve, an approach that is used to model the real lifetime of products, given that some buildings last more than 100 years and some last only 10 years. It is important to note that this is an assumption made under certain circumstances, such as those resulting from a war or other unexpected events, which can lead to significant alterations in the lifetimes of structures. For instance, the bombing of cities can significantly reduce the expected lifetimes of buildings. Another potential influence on lifetimes is policy change. A notable example of this would be the transition from gasoline-powered vehicles to electric cars, which could lead to a significant alteration in the expected lifetimes of automobiles (Ramoni & Zhang, 2013).

2.5.2 Recovered and export end of life scrap

Upon the completion of its utilitarian function, steel scrap is subject to a series of recovery systems, changing per region (Hall et al., 2021; Harvey, 2021). The recovery rates employed in the model undergo alteration across three distinct periods: from 1910 to 2010, from 2010 to 2050, and from 2050 to 2100. The data has been adapted and expanded upon from Dworak et al. (2022), ranging from 58% for metal goods before 2010 to 98% for cars after 2050. The complete list can be found in the supplementary material. The phenomenon of steel loss in the system results in an increasing of stock of unrecovered scrap in the process waste management. This occurrence is characterized by instances such as the sinking of a boat that is not recovered, or the failure to retrieve scrap from landfill. It is assumed that 100% of fabrication and production scrap is recovered. The validity of this assumption is confirmed by experts of Tata Steel Europe upon site visits. It is specified that the scrap in question consists of steel in the form of intermediates and offcuts, and not dust or slack arising from the processes.
The export of end-of-life scrap is defined as the process of exporting goods to countries outside of the European Union. Within the model, it is hypothesized that 30% of cars and 70% of trucks are exported. For other end-of-life streams, it is assumed that no exports of end-of-life scrap take place.

2.5.3 Production scrap

The production scrap is determined by a percentage of the steel produced, and this figure is used to simulate losses during the process, e.g. at the casting and rolling stages, where the sides of the slabs/sheets are trimmed. The creation of production has been optimized over the past century, with a linear decrease from 23 wt% in 1911 to only 8 wt% in 2017. This parameter has been adapted from Dworak et al. (2022), where it is based on data from Eurostat and world steel statistics (Eurostat, 1970; WSA, 2019).The process of continuous casting has been identified as a primary driver in the reduction of production scrap, with further analysis indicating that this improvement is a key influence. After 2017, the value of 8wt% is utilized for the time span extending from 2017 until 2100.

2.5.4 Fabrication scrap
The scrap of fabrication is dependent on the product being produced and all the product steps taken to produce the product. In this model, the product is defined as the combination of intermediate-sector fabrication scrap factor. To illustrate this, consider the fabrication of a car. During the production of an automobile, for instance, 40% of the cold-rolled coated steel does not ultimately end up in the finished vehicle during the fabrication process. The proportion of this material that cannot be used in the production of the vehicle is referred to as the fabrication scrap. The supplementary material provides a comprehensive list of scrap factors for each sector-intermediate combination. This list is adapted from Cullen et al. (2012b) and Dworak et al., (2022b).

The fabrication scrap and production and forming scrap are further referred the rapport as production, fabrication and forming scrap (PFFS).

Table 2.5. *Quality indicators of steel and scrap. Detailed list of quality categorization of intermediates per sector provided in supplementary material*

Max. content of tramp elements ($\sum Cu, Sn, Cr, Ni, Mo$) in wt%	*Quality category*	*Typical steel intermediates*
<0,18	Q1	Most flat products (colled 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)
>0,35	Q4	Heavy section, light section, rail section, reinforcing bar, hot rolled bar (construction).

2.5.5 Quality of steel intermediates
The quality of steel is defined as the sum of the five most significant elements. These elements are copper (Cu), nickel (Ni), tin (Sn), molybdenum (Mo) and chromium (Cr). This approach, in which the sum of these elements is considered a parameter for steel quality, is a common one ((Dworak et al., 2022; Dworak & Fellner, 2021b; Raabe, Jovicevic-klug, et al., 2024a; Watari, Hata, et al., 2023). This quality indicator systematically categorises the diverse range of steel types, each with its unique composition (often determined by the specific steel mill producing it) into four clearly defined categories. This classification system serves to simplify the intricacies associated with the flows of intermediates, thereby facilitating the modelling of steel and scrap metabolism on a European scale.

In the model the intermediates for every sector off the demand is sorted in a category. In the supplementary material a full overview is available.

2.5.6 Quality of scrap
The quality assessment of the scrap is depending on the origin of the scrap. Fabrication, production, and end-of-life scrap have been defined in Paragraph 3.2. The quality indication for scrap is consistent with that for intermediates (see Table 3.5). For fabrication and production scrap, the model adopts the intermediate quality rating from the end-use sector. The sorting of fabrication and production scrap is conducted at the intermediate level, as outlined in paragraph 3.5.5. It is noteworthy that no losses occur during the processing of this scrap.

The categorisation of end-of-life scrap can be approached through three methods. These sorting methods consist of intermediate level, sector level, or a combined approach. The sorting of the end of life scrap in these separate three ways is documented in the supplementary material for comparison.

The sorting methods employed at the intermediate level involve the separation of end-of-life scrap into its respective intermediates, with this separation being conducted according to the matrix outlined in Paragraph 3.5.5. It is assumed that in this separation step contamination of the specific elements (Cu, Sn, Cr, Mo and Ni) does not occur from coatings, connections or components. These sources are then assumed to be fully neutralized in the sorting step. This can be mechanical sorting or metallurgical purification in the liquid stage.

The sorting on sector level is conducted in accordance with a sector-specific classification system. This categorisation encompasses the contamination arising from factors such as coatings, connections, and components. This approach is exemplified by the categorisation of car end-of-life scrap, which predominantly contains quality 1 intermediates, as quality 4 scrap due to the risk of contamination with copper. This categorisation has been adapted from Dworak et al. (2022), which is based on literature data (Daigo et al., 2017; Hatayama et al., 2014; Igarashi et al., 2007; Savov et al., 2003; Schrade et al., 2006). This finding is consistent with the results of our own analysis of additional literature (Nakamura et al., 2012; Raabe et al., 2024b).

The combined approach is a combination of the previous two approaches. Prior to 2020, it was estimated that the sector level represented 90% of the mass of end-of-life scrap, with the remaining 10% being sorted at the intermediate level. It is projected that this ratio will undergo a linear change over time until 2050, with 80% of scrap being sorted at the intermediate level and 20% at the sector level. This estimation is based on judgement of experts from Tata Steel, the Netherlands (TSN), a company that is engaged in daily research and procurement activities related to scrap. The combined approach is employed to analyse the results.

2.5.7 Production matrix

The incorporation of the production process within the model is achieved through the utilization of a develop production matrix. The input of scrap per batch of steel produced has a detrimental effect on the quality of the finished steel. The qualities of steel and scrap are explained above. Utilising these four categories of steel and scrap, an effort is made to delineate the potential consumption of scrap per produced steel batch for the BF-BOF and EAF processes.

The BF-BOF process data for the input of scrap at Tata Steel, Netherlands is analysed for a period of two years (mid 2022 to mid 2024). It should be noted that this production location is exclusively engaged in the production of steel classified under Q1, thereby providing the relevant data for this particular category. The average input values of scrap qualities can be found in the supplementary material. The necessity to produce specific steel qualities with particular chemical compositions necessitates consideration of the impact of scrap quality, which may present challenges. The presence of tramp elements in specific steel batches can lead to significant challenges, both financially and logistically.

The utilization of scrap material in the BF-BOF process is not primarily optimised for the quality of the scrap itself. Consequently, this optimalisation is constrained by various factors. These include the geometric shape and weight of the scrap, the homogeneity of the supply, and the presence of other contaminants (Compañero et al., 2021; Tata Steel Europe, 2025). The geometric shape and weight of the scrap are of particular significance, as they have been shown to have a direct impact on the melting behaviour in the converter (Compañero et al., 2021; Tata Steel Europe, 2025). A strategy employed to address this challenge involves the incorporation of heavy dens blocks, such as mechanical scrap, into the converter, along with lower density scrap, including packaging scrap. This approach serves to regulate the temperature within the bath, thereby ensuring optimal processing conditions. The process of melting the scrap releases energy in the form of heat, which in turn causes a decline in the temperature of the liquid steel. The homogeneity of supply is defined as the chemical composition difference over time for the supply. If this composition changes over time, the resulting steel batch will also change, and the processing of the steel can be required to change. In the most unfavourable scenario, the batch chemical composition may deviate from the specified parameters, rendering it unsuitable for the intended steel production. Mixed contamination is defined as substances that have an effect on

Table. 2.5. *Production matrix table for BL-BOF and EAF. This is describing the scrap that can be used to produce steel qualities. It is now optimized for low quality scrap input. The rows are the batches of different qualities. The columns are the scrap input of different qualities in percentage of total batch. The scrap input column is the total scrap percentage input for this batch. Target concentration column is the target tramp percentage of this batch in wt%. The maximal concentration is the maximal percentage of tramp elements for this quality category, as described in paragraph 2.5.6.*

Blast Furnace BOF

		Scrap input qualities						
		Q1	**Q2**	**Q3**	**Q4**	**Scrap input**	**Target concentration [wt%]**	**Max concentration [wt%]**
Batch qualities	**Q1**	19%	0%	7%	1%	27%	0,045	0,18
	Q2	3%	0%	1%	23%	27%	0,198	0,25
	Q3	0%	0%	0%	27%	27%	0,275	0,35
	Q4	0%	0%	0%	27%	27%	0,470	0,833

Electric Arc Furnace

		Scrap input qualities						
		Q1	**Q2**	**Q3**	**Q4**	**Scrap input**	**Target concentration [wt%}**	**Max concentration [wt%]**
Batch qualities	**Q1**	41%	1%	3%	0%	45%	0,045	0,18
	Q2	6%	21%	23%	10%	60%	0,198	0,25
	Q3	50%	0%	3%	27%	80%	0,275	0,35
	Q4	47%	0%	2%	51%	100%	0,470	0,833

steel production and may be characterized by increased dust or gas emissions, toxicity or radioactivity.

Moreover, the procurement of preferred scrap is challenging due to the limited available options. The recent market is characterized by elevated demand and prices for scrap materials (Tata Steel Europe, 2025). The primary catalyst for this transformation is the European steel industry's transition towards a higher input scrap-based steelmaking process. This transformation poses significant challenges in terms of optimizing the utilization of scrap materials.

The maximum tramp value for each batch is determined by the quality indication of the steel demand. It is imperative to note that the stipulated maximum value does not necessarily reflect the actual tramp value of the steel batch subsequent to the converter. This value is derived from the production values of Tata Steel for Q1, representing a quarter of the maximal value. This approach enables the calculation of values for other qualities by determining the difference between the qualities, thereby generating a tramp element concentration value for column.
It has been established that the BF-BOF process eliminates 40% of the chromium and 20% of the nickel from the steel bath (TSN experts, 2025) during the oxidation process. However, given the extensive range of scrap materials with their diverse chemical compositions, this reduction could not be modelled.

The base value of the five most prevalent tramp elements in liquid steel is not directly incorporated in the production matrix, but it can be found in the supplementary materials provided by Tata Steel Netherlands for illustrative purposes. The tramp value added to the steel batch from the scrap is only a quarter of the maximal value, leaving ample space for the liquid steel base value. Additionally, there is scope for the incorporation of specific alloying elements to enhance the quality of the steel in a given batch.

In Europe, the BF-BOF route is utilised in 55% of steel production, while 45% is produced via electric arc furnace (EAF) methods (Eurofer, 2023). This distribution is modelled until 2100. The potential evolution of this distribution over time requires further investigation.
For the purpose of this study, the scrap input values from table 3.5 are assumed for the part of EAF steelmaking in this transition. This demonstrates that the production of steel is enhanced by the utilization of scrap materials ranging from 45% to 100%, with a corresponding decline in steel quality. Further research is necessary to ascertain whether these values are representative of European EAF production.

2.6 Material pinch analysis

Material pinch analysis involves the balancing of demand and available scrap over time. The following equation is applied to each category to calculate the yearly supply of scrap utilised in production, the surplus, and the deficit between supply and demand.
Material pinch analysis equation:

$$Sq,t - Dq,t = Rq,t$$

Where:
Sq,t is the supply for a given quality *q* and year *t,*
Dq,t is the demand for the same quality *q* and year *t,*
Rq,t is the resulting balance (or residual) for that quality and year, representing the difference between supply and demand.

In this context, the resulting number, designated Rq,t, can assume a positive, zero, or negative value. This categorisation corresponds to the concepts of import, mass balance, or export, respectively.

3. Material flow analysis results

As the results of trade balance scenario (1) and the BAU scenario (2) are similar, the graphs corresponding to trade balance scenario have been transferred to the supplementary information. The scenarios results are similar because, just like the in the trade balance scenario, the import in the BAU scenario is relative low because it is calculated on the historic average (see paragraph 2.4).

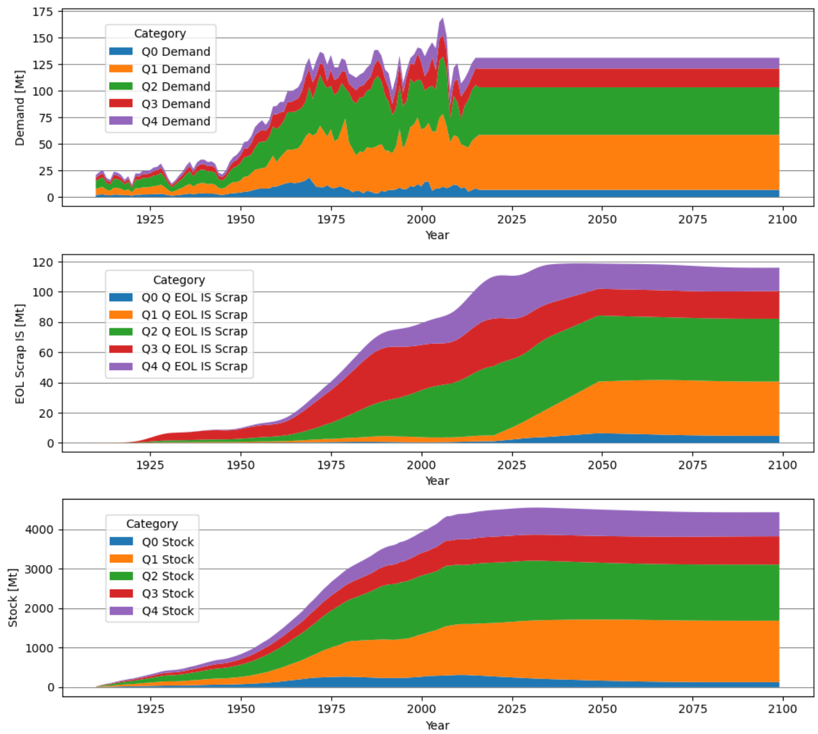
3.1 Steel metabolism

The impact of a high import scenario (3) differs only in terms of production, forming and fabrication scrap (PFFS). Figure 3.1 provides a visual representation of the steel metabolism as demand (inflow), stocks and outflow in two graphs, PFFS and end of life scrap. The end-of-life scrap is the scrap coming free after the use phase, where the product is used for their respective lifetime. The high import scenario has high levels of import of finished steel products and intermediate steel products creating less domestic production of these finished steel products and intermediates. When a product is domestic produced a side product is scrap (PFFS) from the production/fabrication processes, thus with less production/fabrication there is less PFFS. The figure 3.1 shows that this has a significant effect of about 20 million tonnes less scrap available if there is high import. This scrap is mostly high-quality scrap. In the material pinch analysis the effect of the lower availability of scrap on the ability to produce the European products from European scrap is discussed.
Notable is the difference between the historic spiky values and the modelled curves of demand and outflow of PFFS. This is because the values from 2017 until 2100 are modelled according to an expected average demand that is constant. The real demand is likely to be spiky like the historic data as this is the result of the societal complex system. The quality composition of the demand is mostly (more that 75%) high quality steel (Q1 and Q2). The lower qualities of scrap are mainly used in the construction sector (supplementary material C) and used in in other sector with the intermediate hot rolled bar and rail section.

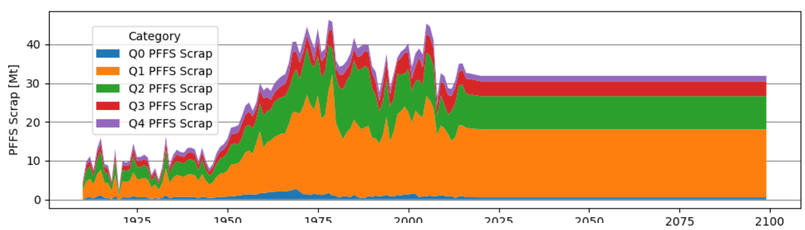
The modelling of the improving sorting parameter for the end-of-life scrap can be seen directly in the end- of life scrap graph (figure 3.1). Specifically, the line of high-quality scrap (Q1) can be seen to increase from 2017 until 2050. This effect shows the improved sorting of the lower quality scrap from the sectors into the higher qualities of the intermediates, resulting in more high-quality scrap.

In the supplementary material L the steel demand is visualized by main sector showing that the construction sector is almost 66% of the total stocks of steel, with the mechanical engineering about 18%. In the demand the mechanical engineering sector has higher percentage than the author expected, being about a 30% of the total demand, this is relatively close the same as the construction (with about 40%) sector. That the construction sector is has a significant higher percentage of the stock can be attributed to the long lifetime of construction steel of average 65 year compared to 17,5 years of lifetime for mechanical engineering steel. In the EOL and PFFS combined scrap that is available (supplementary material L), the mechanical engineering sector is a significant portion of the scrap available of about 25% of the total scrap available, this is quite high compared to the construction sector with a third of the total scrap available.

Results for all scenarios (Demand, EOL scrap, Stock)



Scenario 2: Business as usual (Similar as scenario 1)



Scenario 3: High trade deficit

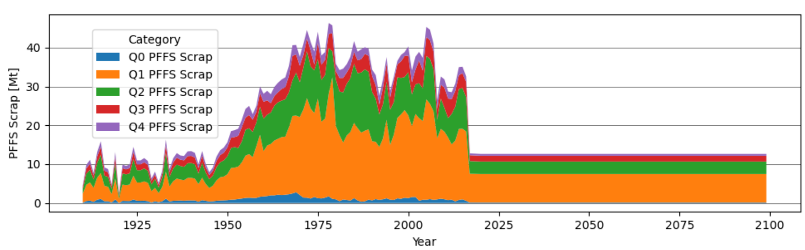


Fig. 3.1. *The steel metabolism for two scenarios (2&3) displayed in 5 graphs; the demand, stock and end-of-life outflow are the same for both scenarios. The production and forming scrap graph is different for the scenario's and is shown twice. As the results of trade balance scenario (1) and the BAU scenario (2) are similar and thus shown in one graph. Scenario 2 is business as usual with 1% fabrication trade deficit and 0,5% production and scenario 3 has 51% production trade deficit and 50,5% trade deficit fabrication. The y-axis values are in million ton (Mt). The qualities in the legend are based on the weight percentage of the sum of the big 5 elements: Q0 = cast iron, Q1=<0,18wt%, Q2=>0,18<0,25wt%, Q3=>0,25<0,35wt%, Q4=>0,35wt%. The figures are from top to bottom, first the demand graph, where is shown that the demand is stable on the 2017 values. This demand is the same for both scenarios and the demand shows the different steel qualities. The second graph shows the end-of-life scrap from finished steel products that is recovered, with improved sorting on intermediate level from 2017 to 2050. Here is also the quality of different scraps shown, with the improved sorting showing in the increase of Q1 scrap of the flows shown. The third graph shows the accumulation of steel in the stocks, both the same for the scenario's, showing the composition of the stock. The fourth graph is different for the two scenarios', showing the impact of high net import trade on the production, forming and fabrication scrap (PFFS). Here in the high import scenario (S3) the PFFS coming available is about a third lower due to import of intermediates and finished steel products, where if they were produced domestically there would be PFFS scrap available.*

3.2 Results material pinch analysis

The material pinch analysis is describing the available scrap relative to the demand of steel, and this for each quality category separately. The demand is sorted in the quality categories based on the intermediate that is used in every sector and the available scrap is sorted on a specific sorting method described in the method section. This is basically describing the efforts of the scrap industry to sort the scrap better on intermediate level instead of a more clustered general sector level. The results in figure 3.2 shows a line for every category with positive and negative values for the period of 1911 to 2100. If the value is negative this describes a shortage, and if the value is positive this describes a surplus. The cast iron flow (Q0) is not considered in this analysis as the data on production characteristics was not further researched in this study.
The figure 3.2 shows the material pinch analysis for on direct mass balance of demand of steel and supply of scrap. This is the graph with the title including without production matrix. This is thus describing a scenario where there is no added primary steel made from iron and al demand

Scenario 1: Zero trade deficit &
Scenario 2: Business as usual

Scenario 3: High trade deficit

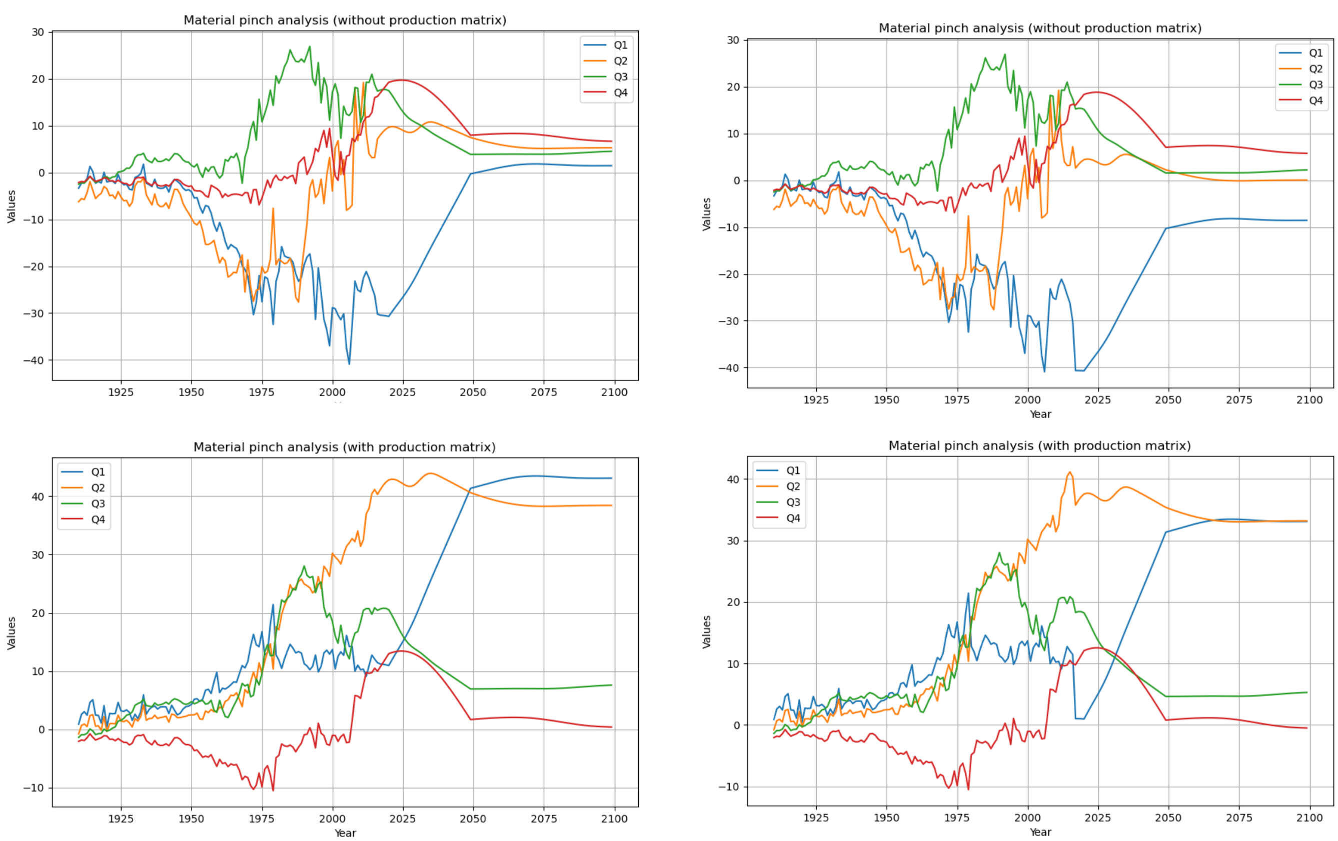


Fig. 3.2. *Material pinch analysis over time for scenario 2, business as usual, and scenario 3, high import, for two options: 1) Excluding the production matrix, 2) including production matrix. The production matrix is the current distribution of production technologies with their respectively scrap uptake (55% BF-BOF and 45% EAF of total EU steel production). This production matrix shows basically the capacity of using scrap in our steel process. The Scenario 1 results is relocated to the supplementary material as these are too similar to scenario 2. The figure is showing the available scrap minus the demand for the four qualities. The graph show positive and negative values with positive value being more available scrap from domestic sources then demand of specific quality of scrap. This overshoot is thus available for exports of scrap. The negative values are when there is more demand of this quality of scrap then available from domestic sources. This shortage is then imported for production. The legend shows the four qualities categories defined as sum of big 5 elements in wt% (Q1= <0,18, Q2 = <0,25, >0,18, Q3 = 0,35, <0,25, Q4=>0,35 (source: Dworak et. al., 2022). Q0, being cast iron, is not considered in this analysis as the data on production characteristics was not further researched.*

is provided via scrap-based steelmaking. The graph with the production matrix in the title in figure 3.2 shows the mass balance of the demand and supply of scrap steel.

3.2.1 Impact of trade

The scenario with business-as-usual trade shows that after 2050 there would be a balance between the supply of scrap and the demand for the steel qualities. This is based on a mass balance of the scrap available with the demand for every quality category. This means that, if all steel production in the EU would be done with EAF and the domestic trade and transportation of the scrap would not interfere, the steel scrap would be sufficient quality and quantity meet the demand via only remelting the scrap. In this situation there would be no need for primary steel from iron ore.

In the high import scenario a shortage of high-quality scrap (Q1) develops. This illustrates that European goal to have a circular steel industry within the coming decades is not possible with a high trade deficit on intermediates and finished steel products. This scenario is modelled with the average net trade balance of the period 2010 to 2017, this is close to zero as described in paragraph 2.4. To achieve this balance the improved sorting plays a crucial role as can be seen that in 2017 the high-quality scrap (Q1) is at a 30 million ton (Mt) shortage but over time the improving is sorting will cause a surplus of 2,5 Mt after 2050.

The second highest quality scrap (Q2), from 2017 onwards, the surplus in the high import scenario is lower than in the business-as-usual scenario, peaking around 2030 at 5 and 12 Mt, respectively. In the high import scenario, the value stabilises at a shortage of around 0.6 Mt for Q2. For the third scrap quality (Q3), the surplus is also lower compared with scenario business as usual, peaking at around 1.3 Mt in 2050, before gradually rising to 2 Mt by 2100. Finally, the lowest scrap quality (Q4), the overshoot is slightly lower at the peak and stabilises also lower, with a difference of approximately 3 Mt, comparing the high import scenario with the business-as-usual scenario

3.2.2 Impact of European steel production methods

As described in paragraph 3.2 the scenario 2 with business-as-usual trade shows that after 2050 is a balance between the supply of scrap and the demand for the steel qualities creating the potential for a full closed circular economy. As described there would be the need for the development of an EAF scrap-based steelmaking industry. This is currently not the case as 45% of the total steel production in Europe is made with EAF, and 55% with a Blast Furnace Basic Oxygen furnace (BF-BOF). And of the EAF production sites these are not always a full scrap based. If this would be considered through considering the current steel production methods via the develop production matrix, the current potential scrap consumption for new steel can be estimated. Comparing this with the availability of steel scrap per quality in the material pinch analysis, the results are quite different.

The results for scenario business as usual in figure 4.2 (graph titled with production matrix) show that there would always be too much scrap available to be used in the current production methods. This would mean that to align with the goal of circular steel industry the current production mix should be shifted to scrap-based EAF steelmaking, considered that the sorting of scrap is improving accordingly. Although the lowest quality scrap (Q4) is negative until 2010 this can be substituted with higher qualities scrap (Q1/2/3) as these are lower in unwanted elements.

The improved sorting is clearly visible in the results showing the growth of available high-quality scrap (Q1) from 2017 to 2050 and a decline of lower quality scrap (Q3 and Q4).

The impact of including the current European production practices on the material pinch analysis can be described in two elements firstly, it leads to a higher surplus for all scrap qualities, and secondly, it results in a lower demand for scrap. The reason for these results is straightforward: as described in the methods section (paragraph 2.5.7), there is a primary steel inflow for making steel with the current production technologies. This mixture is estimated depending on the production techniques (BF-BOF and EAF) to change between 27% and 100% of scrap input. This results in a lower demand for scrap, especially the higher qualities of scrap (Q1 and Q2). In contrast, the lower qualities (Q3 and Q4) exhibit a lower overshoot, and in cases of high imports (S3), a shortage may even be anticipated.

When there is a deficit of a scrap category this is modelled to be imported from outside of the EU. Similarly, a surplus of scrap per category is exported to outside of the EU. The import and export are visualized in the supplementary materials M.
In both scenarios there will be high export of scrap, with only a difference of 10 Mt after 2050 between scenario 3 and scenario 2. But the import in the high trade deficit scenario 3 shows that there is a need for import of high-quality scrap (Q1) after 2050. Making Europe dependent on scrap import from outside of the EU.

The results show that the export of all scrap (sum of all categories) is significant with circa 90 Mt after 2025 in scenario 2 business-as-usual. This value is modelled with the inclusion of the current EU production capacity (production matrix). The import in the business-as-usual scenario 2 with current production capacity is after 2017 zero, with historically modelled import of low-quality scrap (Q4).

When the EU production capacity is not considered the export of all scrap (all scrap qualities) is around 18 Mt after 2050 but shows a peak on more than 45 Mt in 2017, with a decline when the sorting is improved. The import of scrap in scenario 2, without production capacity, shows that after 2050 there is no import needed as the sorting is then improved to 80% on intermediate level. But before 2050 there was a need of importing the high-quality scrap (mainly Q1) for the production of steel in Europe.

Similar results can be observed in the high trade deficit scenario 3 with production capacity (Production matrix), with a export around 70 Mt after 2050. The import in this scenario with the production capacity shows zero but without production capacity (being the production matrix) shows a steady import just below 10 Mt of high quality scrap (Q1).

4. Discussion and recommendations

The results show that for a circular steel industry and system, the EU should move to scrap-based EAF steelmaking with minimal or no iron ore input. This finding is specifically conditional on the availability of sufficient scrap, the improvement of the quality of this scrap and innovation in scrap-based steelmaking. In order to ensure sufficient scrap (all individual qualities), it is essential that in the EU the sorting of scrap improves to a minimum of 80% at intermediate-to-intermediate level, and that a trade balance on steel containing products is established. The innovation of EAF technologies to enable the production of all steel qualities by scrap-based-EAF is of critical importance, given that this is still not commercially achieved (see paragraph 4.4).

A further general recommendation is that a sensitivity analysis be conducted to enhance the reliability of the results by describing the impact of individual assumptions. This is not included in the present study due to limitations in time and resources. The preliminary approach to this sensitivity analysis involves modifying the input parameters and subsequently analysing the resulting effects (refer to the supplementary materials for a more detailed approach).The model assumptions on parameters aim to depict the reality under different scenarios.

In this chapter, an discussion is provided on the following key areas: demand, steel and scrap sorting, trade, and steel utilisation in production.

4.1 Demand

The demand variable indicates constant demand after 2017 on the 2017 value, which does not align with the projected decline of demand estimated in Western economies (IEA, 2023; Pauliuk et al., 2013; Watari, Giurco, et al., 2023a). However, as explained in the methods section, the values for this saturation quantity and timeline are distributed, with demand in 2017 remaining within the established limit. Consequently, it is essential to acknowledge the potential for fluctuations in demand and the resultant scrap flows from end-of-life products in future.
Historically, demand for materials has been known to be disrupted by factors such as wars (Krausmann et al., 2009) and a pandemic (Zanoletti et al., 2021). Such events have the potential to disrupt supply chains or to precipitate a sharp change in demand. Consequently, this research provides a starting point for further research on the impact of demand. Another area for discussion is the potential for a significant decline in steel demand, should the sustainability transition of more efficient steel use be implemented in the domain of product and system design. A notable illustration of this transition is the shift from a concrete-and-steel-based architectural paradigm to a wood-based alternative (Abed et al., 2022). Another example is the transformation in mobility patterns (Ceder, 2021). These shifts have the potential to exert a substantial impact on steel demand, given that these two sectors currently account for nearly 50% of the total demand in Europe. The future trend of the steel consumption in Europe should be further researched and implemented in the develop model to develop the best circular steel strategy for Europe.

4.2 Steel and scrap sorting and accumulation

A primary constraint of the model pertains to the accumulation of tramp elements within the scrap. The model has been modified to demonstrate that when scrap is sorted at an intermediate-to-intermediate level, it can be utilised to produce steel with a lower or equivalent level of tramp elements. This theoretical possibility is embedded within the simplified model, which encompasses only four quality categories. However, it can be argued that this is not feasible in practical applications. To have intermediate-to-intermediate sorting in real life there would be a need of the same amount of scrap categories as there are chemical compositions of alloys. These are numerous as these chemical compositions are changing historically and geographically.

There could be an effort to sort them into groups with relative the same chemical composition and then melt it into new steel but then there would always some accumulation of tramp elements. The number of groups for the separation is directly proportional to the reduction in accumulation, thereby extending the lifespan of the steel in its current application.
Moreover, in reality, there are other potential sources of pollution, including but not limited to: coatings, connected components, processes, technologies, and dust. These additional elements contribute to the presence of undesirable contaminants, thereby limiting the number of times that steel can be recycled at the same function level.

The costs associated with the sorting and cleaning of scrap further restrict the maximum number of cycles that steel can be recycled. This is due to the fact that each additional step increases the overall cost of steelmaking from scrap. Further research is required in this area to optimise the costs of sorting and cleaning processes and integrate it into steelmaking. Even for elements that can be extracted from scrap using available techniques, the costs of the process can prevent this from being done on a large scale, as illustrated by the cleaning of scrap from zinc (Tata steel experts, 2025).

When discussing the costs of the cleaning and sorting, using scrap steel with a chemical composition with the target steel quality could reduce steel making costs by reducing the costs of virgin alloy materials (Ohno et al., 2017b). These alloy elements are generally much higher priced then steel but in steel scrap they can be bought for a price generally lower than steel/iron, providing a potential businesses case.

In Cullen et al., (2012) the global flows of steel in society were analysed. In this study we used the global values for categorisation and material intensities from Cullen and assumed these would be similar in Europe. However, these values may differ from those observed in global streams. However, the steel industry is characterized by a variety of standards and practices that differ globally, with notable examples including resource efficiency (Gonzalez Hernandez et al., 2018) and carbon footprint (Hasanbeigi et al., 2016). This could cause that in the EU the categorization of steel and scrap flows would be different, shifting the demand and scrap availability of qualities. This doesn’t have to be a problem and could balance itself as the demand and scrap available shifts but when including the European production capacity (production matrix) it is not certain. Only through further research this could become clear.

4.3 Trade

At the time of writing, the trade scenarios of finished goods represent a particular point of discussion in the global context, where the United States President, Donald Trump, has initiated a policy of threatening the mutual trust between countries and continents. A method employed in this trade war is import tariffs, and it is highly probable that international trade will undergo significant change in the coming years. Consequently, the quantification of the impacts of these trade changes is a relevant consideration.

In the scenarios in this study the assumption is made that the traded goods that are imported and exported in the EU, are existing of equivalent steel quality and material intensity to those produced in the EU. This is in the real world not always the case. For instance, as demonstrated by (Bian et al., 2015) Chinese-imported automobiles may comprise different steel types from those utilized in European production. This discrepancy could potentially impact the quality of scrap that is subsequently coming free in the end-of-life of these vehicles. In addition, the design of products intended for recyclability (Ghadimi et al., 2022) exerts an influence on the prevailing categorisation of products. In addition, the innovation over time is not considered. To illustrate this point, consider the scenario of that a car manufactured in 2005, which is now regarded as containing the equivalent quality scrap as a car produced in 2050. But there could be major differences e.g. as the gasoline cars change to a electric driven vehicle. Further research is necessary to establish the impacts of the change of product design in categorization of steel in demand and steel scrap available.

4.4 Steel scrap utilization in production

The production methods in Europe are currently modelled as a static parameter of 55% BF-BOF and 45% EAF. However, considering the plans for decarbonisation and green steel, the goals are set is to phase out the BF-BOF and increase the EAF share. Further research is required to incorporate this trend in the model and align it with the circularity targets.
Another element of discussion related to the steel production is the input of scrap. The assumed input of scrap per category for different steel qualities is based on expert judgement and historic data from Tata Steel, Netherlands (TSN). Nevertheless, as outlined in Paragraph 1.2, there are multiple ongoing initiatives to innovate production processes for various reasons, including scrap input. These improvements will change the scrap use in steel production. Further research is necessary to incorporate more characteristics of these modifications in the model. Further research in this area is required to focus on the building of a dataset with the input of multiple steel plants throughout Europe.

The regional availability of scrap is another limiting factor. TSN is currently generally procuring scrap from within a range of about 500. In the model for this stduy there is assumed that all scrap is optimal distributed and used according to the production matrix. The current system of scrap distribution is changing per region and lacking transparency and coordination on quantity, quality and origin. This, in turn, impacts the potential for optimising scrap input in a circular economy, thereby causing the downcycling of qualities. The scrap market should be optimised to ensure the effective distribution of scrap to various steel production locations. The implementation of such a strategy would exert a considerable impact on the long-term sustainability of the steel industry. This is now optimized for the input of low-quality scrap causing the distribution of the tramp elements in the low-quality steel between all steel categories. This is beneficial in the situation of closing the circular steel loop as early as possible but causes a higher tramp element content in the high-quality steels.

With the current four quality categories this is not yet a problem as the boundaries for tramp elements is simplified. But in reality, this could cause challenges with producing particular steel grades. Thus, there should be further research on what is actual the best approach for scrap input of steelmaking. This could possibly be a quality-to-quality approach where high quality steels (Q1 intermediates) are only made with high quality scrap (Q1 scrap). A total impact analysis of the steel production in Europe considering the scrap input needs to be further researched as the reduction carbon emissions is not taken into account in this analysis.

4.5 Europe circular steel strategy

As articulated in the "Future of the European Competitiveness" report (Draghi, 2024),the European steel industry is confronted with dual challenges: escalating costs associated with decarbonisation and the deleterious impact of global overcapacity, notably from China. This has resulted in an escalating influx of steel imports and a diminishing market share for the domestic steel industry. The declining steel production and shrinking market, in conjunction with high energy costs and declining demand, present significant challenges to the investment decision-making process for green technologies, such as green hydrogen, due to the absence of a financially viable business case. The introduction of a carbon border adjustment mechanism has

the potential to induce a carbon leakage scenario. The European Union and its member states are facing mounting pressure to address these challenges, which in turn impacts the potential for innovation in the field of sustainability. The topic of scrap recycling in a circular economy is a pertinent one in the European competitiveness context as it is directly related to material independency and decreasing costs and environmental impacts of steel production.
The formulation of a circular steel strategy for the European steel industry is imperative to reach the maximal material efficiency in recycling and maximal environmental emission reductions. An important consideration is to either optimize the steel industry and recycling for the global steel system or only for the European steel system.

A question to answer is what the responsibility of the Global North in the global steel system is. The global North, including Europe, is projected to have an adequate supply of scrap metal to meet its anticipated steel demand by the year 2050. Utilising the EAF process in conjunction with optimal sorting techniques has been demonstrated to be a more cost-effective and environmentally friendly approach when compared to the BL-BOF methods (Watari, Giurco, et al., 2023a).

In contrast, regions classified as part of the global south are projected to derive a mere 5% of their demand from domestic scrap sources in 2050. This scenario poses a significant challenge, as it leaves the region with limited domestic scrap availability, forcing the use of more expensive and polluting technologies to produce steel. The absence of a strategic approach to address this imbalance could hinder the achievement of global climate targets.

The primary cause of climate change as global warming is the historical carbon emissions of the global north (Watari et al., 2023). Consequently, there is an urgent need to devise a strategy that not only utilises and optimises scrap input within Europe but also fosters the development of green primary steel production methods globally. These production methods for producing primary green steel should ideally be developed in cooperation the growing economies of the global south to achieve globally the net zero emission goal in 2050.

In a recently initiated research project in the Netherlands, the transition of the steel industry has been identified as a subject for investigation. The overarching objective of this project is to formulate a comprehensive strategy for both the European and the global steel industry, with a view to promoting sustainable development. This interdisciplinary initiative involves collaboration between government entities, academic institutions and the steel industry, with the aim of developing a strategy that will ensure the long-term competitiveness and sustainability of the steel sector.

5. Conclusion

This study utilised a dynamic material flow analysis (dMFA) to quantify the steel and scrap metabolism in Europe, with a particular focus on the impacts of a trade, sorting of scrap and current European steel production methods with respect to scrap processing capacity. The research encompassed three distinct scenarios: no trade deficit, business-as-usual trade, and high trade deficit. The study incorporated an improved sorting of scrap over time, modelled based on sector or intermediate steel quality. Additionally, it quantified the impact of current European production techniques on the balance of scrap availability and steel demand through a material pinch analysis. The following key insights emerged from the case study:

- For circular steel, the European steel industry needs to shift to EAF steelmaking in combination with high domestic European production and fabrication of steel products,

causing a minimal trade deficit of steel containing products. The findings indicate that in instances where the trade deficit is high, there is a shortage of high-quality scrap, thereby constraining the potential for the closed-loop recycling of steel.
- To achieve a balance between available steel scrap and demand qualities in a low trade deficit scenario it is essential to have an improved sorting off scrap up to 80% of the end-of-life steel scrap on intermediate level. In the present analysis, the recycling process is modelled to be achieved by the year 2050. However, as soon as this level of sorting is attained, the loop can be closed.
- The optimisation of scrap utilization in steel production necessitates the formulation of a strategy for the effective distribution of scrap within Europe. This strategy must align the available scrap with the production methods of individual steel mills to prevent downcycling practices and to curb the future accumulation of tramp elements.
- In order to reach the global net zero goals the European circular steel industry strategy must encompass the responsibility of the Global North in climate change. This responsibility translates to the steel industry in the distribution of knowledge, technology and materials to aid the sustainable development of the steel industry in the global south.

Further research is required into the assumptions underpinning this study. A sensitivity analysis would provide an overview of the parameters with the most significant impact and generate more reliable results. In addition, the categorisation of steel products, intermediates and scrap should be the subject of further research, as it is currently based on general global data. The improved sorting of scrap also needs to be the focus of further research, as there is currently no data available on current practices.

The model, code and the relevant data can be found in the supplementary materials or by contact of the author.

5.1 Acknowledgements
The author gratefully acknowledges the helpful comments and suggestions of the reviewers. Especially the supervisors who helped with their guidance to bring the research to the final result.

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