The role of steel scrap as a secondary material and potential source of CRMs: Case study of The Netherlands under an EU context

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Executive summary

The Netherlands Materials Observatory (NMO) plays a key role in strengthening the resilience of the Dutch and European economies by collecting, managing, and analyzing data on critical raw materials (CRMs) and their supply chains. In collaboration with government bodies, industry, and research institutions, the NMO provides strategic insights into CRM availability and supply risks, supporting informed decision-making. A key focus is on enhancing recycling and circularity to meet the EU's Critical Raw Material Act (CRMA) benchmarks. Through targeted case studies, the NMO explores the potential of secondary materials and waste streams to contribute to CRM recovery, offering valuable guidance on recovery pathways, challenges, and feasibility in meeting recycling benchmarks. This case study focuses on steel scrap and presents an overview from the Dutch and European perspectives.

Steel scrap contains valuable Critical Raw Materials (CRMs). However, the current theoretical potential to recycle these elements individually and contribute to the 25% CRM recycling benchmark in the CRMA is limited. Economic, technical, and market dynamics drive these limitations. Nevertheless, targeted support for advanced separation technologies could serve as a first step to unlock future CRM specific recovery potential.

To support the Netherlands' and the EU's transition toward higher use of steel scrap, policymakers must address the rising demand for high-quality steel scrap, which can require increased imports due to limited domestic availability in certain regions if more efficient sorting mechanisms are not introduced to avoid the downcycling of this feedstock locally.

Challenges can arise for existing export hubs (Port of Rotterdam) and companies if EU export restrictions reduce flows to non-EU countries. However, this can also encourage steel producers and steel scrap companies to invest in sorting mechanisms with the support of policy incentives.

At the EU level, this trend presents a strategic opportunity to invest in advanced scrap upgrading technologies and incentivize innovation to improve feedstock quality, reduce contamination, and enhance circularity. Policy interventions should promote long-term partnerships between steel producers and scrap processors, ensure competitive access to low-carbon electricity, and develop off-take mechanisms for various scrap qualities to help stabilize the market.

Coordinated strategies are essential to manage scrap quality, energy costs, and export pressures, ensuring the EU steel industry remains resilient, competitive, and aligned with strategic autonomy, circularity targets and decarbonization goals.

Contents

1 Introduction

The Netherlands Materials Observatory (NMO) collects, manages, and provides data, information, and knowledge about critical raw materials and supply chains. In doing so, the NMO contributes to a resilient and robust economy and society. The NMO works together with the Dutch national government, companies and research institutions in the Netherlands and abroad. The NMO provides insight into the supply and availability of these critical raw materials in the Netherlands and the European Union (EU). An enhanced understanding enables policymakers and businesses to better respond to risks associated with supply chain disruptions.

The NMO works with partners from the recycling value chain and the research community to analyse how the Netherlands (and neighbouring countries) can contribute towards increasing recycling contributions and, by extension, the Critical Raw Material Act (CRMA) benchmarks. In addition, it works closely to understand the role of circularity in strategic value chains.

As part of the recycling and circularity theme, the NMO is conducting a series of case studies to understand the context and background of different Dutch waste streams, end-of-life of product groups, and secondary materials. These case studies also provide relevant information about CRMs present in those materials/waste streams and discuss potential recovery pathways and challenges for such CRMs. In addition, it explores the feasibility of such materials/waste streams to contribute on an elemental basis to the CRMA recycling benchmark. This case study focuses on steel scrap.

The global and Dutch steel (scrap) loop acts as a carrier for large quantities of Critical Raw Materials (CRMs). CRMs such as vanadium (V), niobium (Nb), tungsten (W), and cobalt (Co) are intentionally introduced during the steel production process to deliver a wide range of steel types. To illustrate, by all worldwide end uses and applications, steel consumes approximately 93% of vanadium (V), 92% of Niobium (Nb), 85-90% of manganese (Mn), 70% of nickel (Ni), and 15% of tungsten (W) (SCRREEN, 2020a, 2020b; Trasorras et al., 2016; USGS, 2024a, 2024b). By mass, the steel (scrap) market is considerably larger than any other metal. For example, in recent years, the EU produced on average 147 million tonnes of crude steel per year compared to 2 million tonnes of primary aluminium or 2.6 million tonnes of refined copper (Eurofer, 2025; Gregoir & van Acker, 2022). More than 90 million tonnes of steel scrap are collected on average every year in the EU (Eurofer, 2025). With the recently introduced CRMA benchmark for the EU of recycling at least 25% of its annual consumption of CRMs, steel scrap arises as a theoretical source of CRMs that can potentially contribute to meeting such recycling benchmark for individual elements.

2 Definitions: what is steel scrap?

In the EU, steel scrap is defined within the context of waste management and recycling regulations. The EU's Waste Framework Directive (Directive 2008/98/EC) provides criteria for determining when certain waste ceases to be waste and becomes a secondary raw material, known as "end-of-waste" criteria. For ferrous metals, including steel scrap, these criteria are outlined in Commission Regulation (EU) No 333/2011.
According to Regulation (EU) No 333/2011, steel scrap is defined as "scrap metal which consists mainly of iron and metal" and must meet specific quality standards to be classified differently than waste. These standards are related to[1]:

- Quality of scrap resulting from the recovery operation
- Waste used as input for the recovery operation
- Treatment processes and techniques

Within these standards, it is worth highlighting that the use of steel scrap must be intended as a raw material in the production of metal substances or objects by steelworks or foundries (the steel making process). The scrap must be free from excessive non-metallic content (total amount of foreign materials "steriles" shall be ≤ 2 % by weight). It should not contain hazardous substances, and only waste containing recoverable iron or steel may be used as input for steel scrap recovery.
Steel scrap can be categorized into three groups.

- Round-around scrap (also known as home scrap), which consists of steel waste generated within the steel mill during the production process itself. It is mainly trimmings from slabs, defective castings, or leftover material from rolling operations. Its composition is known and controlled because it never leaves the production facility and is easily reintroduced into the production process.
- Pre-consumer scrap consists of "clean" scrap generated as a byproduct of downstream manufacturing activities, such as in the automotive sector. Its composition is known, and it is most of the time free from contamination. This makes it a high-value raw material that can be easily integrated into the steel production process.
- Post-consumer scrap consists of feedstock derived from products that have completed their life service and have been discarded by consumers or industries. Post-consumer scrap is the most abundant type, characterized by its extreme heterogeneity, high levels of contamination with both metallic and non-metallic materials, and a largely unknown and variable chemical composition (Hundt & Pothen, 2025).

[1] For more information see Council Regulation (EU) No 333/2011 of 31 March 2011 establishing criteria determining when certain types of scrap metal cease to be waste under Directive 2008/98/EC of the European Parliament and of the Council

3 The strategic role of steel

The European steel industry contributes around €80 billion to the EU's GDP and supports over 2.6 million jobs (European Commission, 2025). Steel is an enabler of a wide range of economic sectors, including automotive, construction and manufacturing. Steel scrap plays an important role in the steel industry as it is a primary source of material for this industry. Steel production is generally divided into two routes, Blast Oxygen Furnace (BOF) and Electric Arc Furnace (EAF). The typical scrap input for the BOF production route varies between 15% and 30%, while for the EAF route, it is approximately 100% (Meskers et al., 2023). However, in the upcoming years, it is expected that new EAFs will operate with a share of 30-50% steel scrap in combination with Direct Iron Reduction (DRI) (Van der Weijde, 2025). Figure 1 shows the location of EU steel production sites. Besides being a secondary source of material with high economic importance, the use of steel scrap contributes to resource conservation as it reduces the need for virgin iron ore and coal. Furthermore, depending on the type and end use, steel can contain a wide range of elements, such as copper (Cu), tin (Sn), chromium (Cr), nickel (Ni), vanadium (V), and molybdenum (Mo), some of which are listed in the Critical Raw Materials (CRMs) Act. The transition to a circular economy relies on maximizing the use of secondary raw materials, such as steel scrap. The EU aims to double its circular material use rate by 2030 (European Commission, 2020), a challenging target for which steel recycling can be a key contributor for different economic sectors.

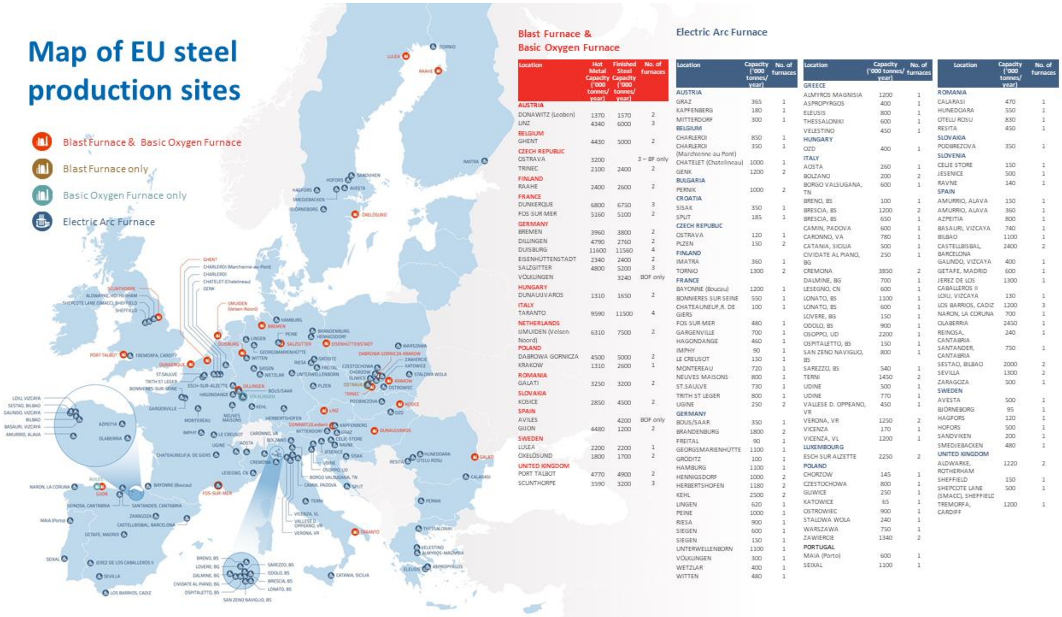

Figure 1 Map of EU steel production sites[2].

[2] Where is steel made in Europe?

4 Steel scrap and crude steel dynamics

Steel scrap dynamics are directly connected to crude steel markets; therefore, a general analysis from the steel scrap perspective alone would fall short of providing a holistic picture.

4.1 Steel scrap

EU steel scrap exports have increased on average by 23% over time (2013-2024), with an export increase peak in 2021 (36%). Steel scrap is mainly exported to countries that rely extensively on EAF routes to produce steel. Approximately (in the most recent years), 16-20% of the total steel scrap collected in the EU is exported (Figure 2). Steel scrap exports have increased, driven by lower domestic demand for steel production and, consequently, lower crude steel production in the EU, as well as higher prices paid for this material in other non-EU countries. Steel scrap is a globally traded commodity, classified under the Harmonized System (HS) Code 7204**,** which encompasses different forms of ferrous waste and scrap. As a commodity, its value is heavily influenced by global steel demand, raw material availability, and energy prices, which significantly impact scrap utilization.

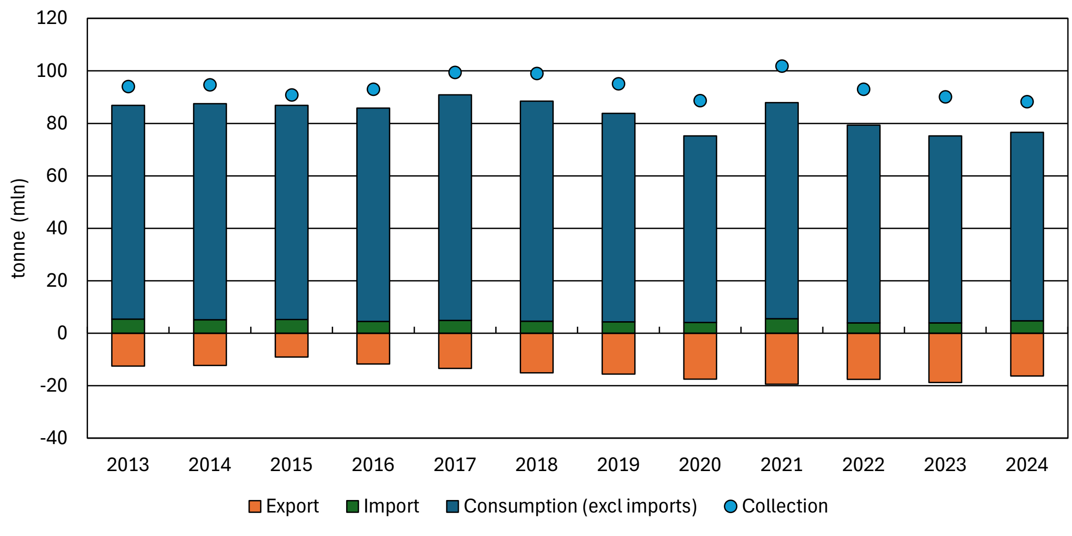

Figure 2 EU's steel scrap market dynamics over time. Data based on (Eurofer, 2025)

The majority of EU steel scrap exports go to Turkey, the largest importer of steel scrap worldwide (Gaulier & Zignago, 2010). The steel industry in Turkey relies mainly on electric arc furnaces (EAFs) and pays a premium price for steel scrap compared to domestic prices in the

EU. To illustrate, the price of steel scrap in Turkey (in May) was around 321€[3] per ton (including freight costs), while in Germany it stood at 297.5€ per ton and in Italy at 315€ per ton. However, note that in several occasions, European scrap dealers pay the Turkish price minus the additional transport costs (Wout Kusters, 2025) Lower shares of EU steel scrap are exported to India, Egypt and Pakistan. The EU has implemented new policy mechanisms to regulate the export of steel scrap. According to the new amendment to the Waste Shipments Regulation (WSR), the export of steel scrap to countries outside the OECD will be allowed only if those countries apply for consent and demonstrate their ability to manage waste effectively (European Parliament and the Council of the European Union, 2024). These amendments could reduce the current steel scrap exports to countries such as India, Egypt, and Pakistan in the near future.

The Netherlands is one of the world's leading exporters of steel scrap, as reflected in the high negative trade balance shown in Figure 3. The negative trade balance indicates that the total amount of exports exceeds the total amount of imports, suggesting that the Netherlands earns more from the steel scrap trade than from its internal use of steel scrap, and has a high demand for this product in the international market. The trade balance for the Netherlands has varied between -2.7 million and - 3.7 million tons of steel scrap in recent years. The Netherlands has accounted for, on average, 9% of worldwide stainless steel scrap exports and 6% of worldwide steel scrap (n.e.c. in heading no. 7204), as shown in Table SM 1 in the Supplementary Material (SM).

The Netherlands stands out as a leading exporter given the advanced developed industrial and post-consumer waste collection system of steel at the end of life of products in sectors like construction and automotive (see section circularity potential), a domestic steel industry with limited scrap consumption capacity (see section use of steel in the NL), and the logistical advantage of the Port of Rotterdam (PoR). The PoR serves as a major logistical hub for the aggregation, shearing, and shipment of steel scrap. The port has dedicated terminals (with specialized infrastructure) for handling and processing large volumes of scrap metal, not only from the Netherlands but also heavily influenced by neighboring countries, especially incoming material from Germany.

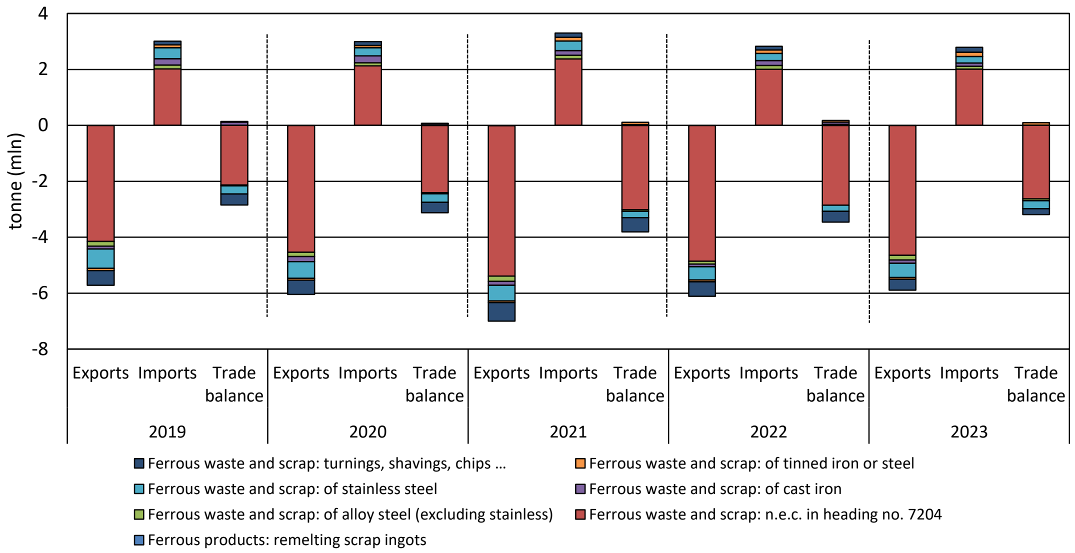

Figure 3 Dutch steel scrap, export, imports and trade balance. Negative values reflect feedstock leaving the country. Data based on (Gaulier & Zignago, 2010)

[3] Global scrap prices have increased in most regions since the beginning of May

The destination of Dutch steel scrap exports varies depending on the type of steel scrap. While the majority of scrap steel classified under Ferrous waste and scrap: n.e.c. in heading no. 7204 is exported to Turkey, followed by Egypt and Germany; other steel scrap types follow a different trend. For example, most of the stainless steel scrap is exported to Belgium and Finland. Both countries are characterized with relevant players and facilities in the stainless steel market, such as the Aperam Stainless EAFs in Genk (formerly ArcelorMittal Stainless) and Outokumpu EAFs in Tornio. A large share of steel scrap classified as ferrous waste and scrap, including alloy steel (excluding stainless steel), is exported to Kuwait and Belgium to a lesser extent.

4.2 Crude steel

In recent years, the EU has produced an average of 147 million tons of crude steel annually, with 84.5 million tons through the BOF route and 62.5 million tons through the EAF route. Total EU crude steel production has decreased by approximately 30 million tons between 2014 and 2024 (see Figure 4). Approximately 41-45% (depending on each year) of total crude steel production is carried out through the EAF route. European steel production has been affected, like other metal industries (Bastein et al., 2024), by persistently high energy prices, competition from low-cost imports (exposure to an uneven international playing field), reduced demand, and global overcapacity[4].

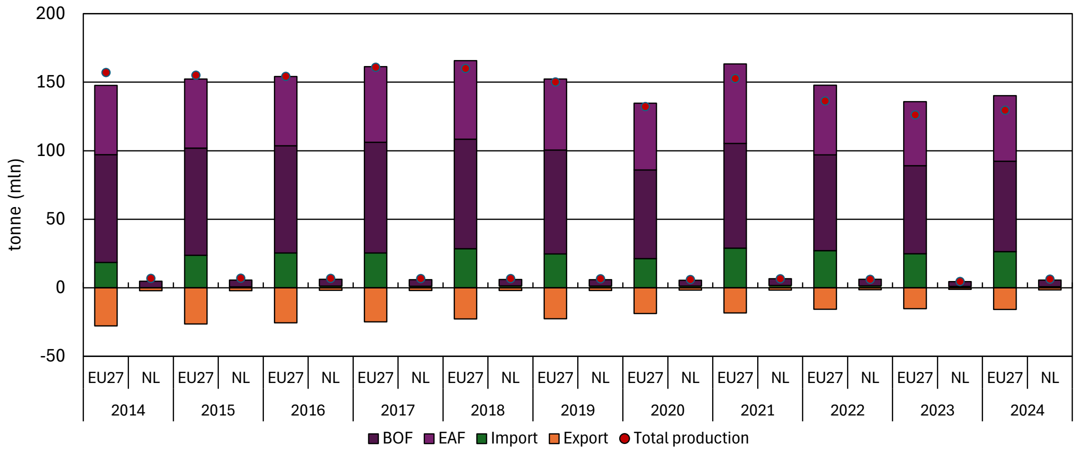

Figure 4 EU and Dutch crude steel production by process, imports and exports. Data based on (Eurofer, 2025)

The overall EU industry steel production capacity has remained underutilized in recent years (Figure 5-A, Y secondary axis) and has decreased over time[5]. Since 2020, the EU steel production capacity has not exceeded 75% of total capacity utilization, with the exception of 2021 (84%). A similar trend is reported for the EAF production route, with a utilization capacity ranging between 61% and 65% (2020-2024), except in 2021, when the capacity utilization was approximately 75% (Figure SM 1in the supplementary material). Generally, steel plants don't operate at their full capacity; for instance, the EU steel industry has been operating at 67% of its total capacity (driven by different factors such as lower demand and energy prices) in 2024, which is below the expected targets. The EU appears to be facing a worsening overcapacity issue, partially driven by global market dynamics and a structural imbalance between global supply and demand.

[4] Latest OECD global overcapacity data show ever-worsening trend confirming the urgent need for strong EU steel post-safeguard measures, says EUROFER
[5] Capacity utilization is defined as total steel produced in the EU over the total installed capacity (BOF and EAF)

Scrap steel consumption has followed a proportional trend to crude steel production. Between 2013 and 2024, steel scrap consumption in the EU decreased by approximately 10 million tons (See Figure 2). However, the relative share of steel scrap consumption in the EU has remained constant over time (Figure 5-B). In the last decade (2015-2024), steel scrap consumption over total crude steel production has varied by less than 4% on an annual basis. Steel scrap collection rates appear to follow a proportional trend to EU steel capacity utilization (BOF + EAF route), as shown in Figure 5-A, suggesting a degree of association between the two parameters and highlighting the importance of steel scrap as a key feedstock for the EU steel industry. Note that steel scrap, besides being a source of material, is also used in the BOF route as a cooling agent to absorb the excess heat.

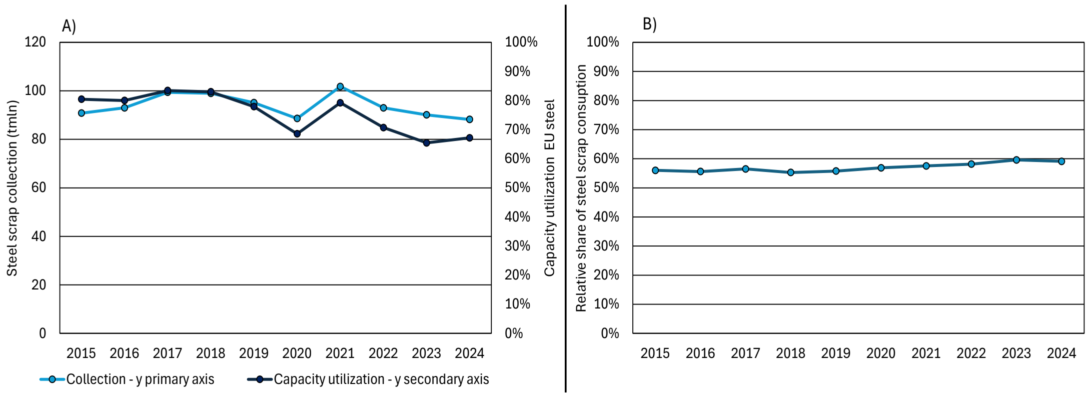

Figure 5 A) steel scrap collection in the EU on the Y primary axis, steel capacity utilization for the EU (BOF and EAF) on the Y secondary axis. B) relative share of steel scrap consumption. Data based on (Eurofer, 2025)

5 Circularity potential

According to the World Steel Association[6], the majority of steel is used in the construction sector (52%), followed by mechanical equipment (16%), automotive (12%), and metal products (10%). The collection rate of steel at end-of-life in the EU is high, typically in the range of 80% to 95%, depending on the sector. To illustrate, the recovery rate by weight in the EU in Construction and Demolition Waste (CDW) is around 89% (varying on a member state level); steel has an average contribution of 4.9% to CDW and it is already regularly separated from CDW to a large extent, given its high market value (Caro et al., 2024). For automotives, in 2022, 94.4% of the material (by weight) was recovered in light vehicles coming to the end of life within the EU (Eurostat, 2024). Stainless steel, widely used in metal products and industrial uses, currently exhibits over 90% collection rates at the end-of-life in the EU (EuRIC aisbl, 2020). The high collection rates of steel at the end of life in products across different sectors indicate a developed scrap metal industry and infrastructure, suggesting that a low availability of potential material (in stock) is not currently being collected. Note that the availability of steel scrap at a certain point in time is directly proportional to the past production of steel and ongoing collection efforts when steel products (application) reach the end of their life.

Reducing steel scrap exports has the potential to improve capacity utilization, but the actual benefit is likely more modest when accounting for the quality of the exported material (see sections Steel scrap quality). This suggests an overcapacity of steel production facilities in the EU when compared to the local availability of high-quality steel scrap. In the near and long term, the role of high-quality steel scrap becomes more central to the EU steel decarbonization efforts and material dependency. This is evidenced by the number of EAF announced projects (some with a combination of Direct Iron Reduction – DRI[7]) with support from national governments and EU funding, such as the ArcelorMittal Gijon plant (Spain)[8] and the Bremen (Germany) facility[9], The Voestalpine facility in Austria[10], Saarstahl facilities in France and Germany [11]As a result, demand for high-quality steel scrap is expected to rise. However, the success of these projects is highly connected to energy prices and not only to feedstock availability. To illustrate, the ArcelorMittal Bremen facility conversion project has recently been dropped because of energy prices[12].

Steel producers have been increasingly acquiring scrap yards in recent years, indicating a vertical integration in their operations from a feedstock perspective, potentially securing access to high-quality steel scrap and reducing their exposure to volatile markets. Note that despite both being part of the same steel value chain, steel producers and scrap yards are generally different stakeholder groups. ArcelorMittal has acquired several scrap yards such as

[6] Steel use by sector - worldsteel.org
[7] DRI is produced by reducing iron ore (pellets or lumps) without melting it, using a reducing gas, traditionally natural gas and projected to be replaced with green hydrogen. DRI - EAF system generally have 70–80% scrap + 20–30% DRI or Hot Briquetted Iron (HBI) imput
[8] ArcelorMittal plans major investment in German sites, to accelerate CO2 emissions reduction strategy and leverage the hydrogen grid | ArcelorMittal
[9] ArcelorMittal starts the construction of an electric arc furnace at its Gijón plant | ArcelorMittal
[10] Green steel in the EAF from 2027 - greentec steel
[11] Next step in the transformation: Central plants ordered for Power4Steel – Europe's largest decarbonization project
[12] ArcelorMittal drops plans for green steel in Germany due to high energy costs | Reuters

the Riwald Recycling (Netherlands) with an annual capacity of 330,000 tonnes of ferrous scrap[13], several facilities from ALBA International Recycling (Germany) with a combined annual capacity of 400,000 tonnes[14], and Zlomex (Poland) with an annual capacity of 400,000 tonnes[15]. Other examples include the acquisition of Must-Metalle-Container-Recycling GmbH by the Salzgitter Group in Germany, aiming to facilitate the use of high-quality steel scrap in their Salzgitter BOF steel plant[16], and the Sidenor acquisition of Aguilar Metal Recycling (AMR) and Miguel Martin scrap yards in Spain[17].

[13] ArcelorMittal acquires Dutch scrap metal recycling business Riwald Recycling | ArcelorMittal
[14] ArcelorMittal acquires German steel scrap recycling businesses from Alba International Recycling | ArcelorMittal
[15] ArcelorMittal acquires Polish scrap metal recycling business Zlomex | ArcelorMittal
[16] Salzgitter Group expanding regional scrap recycling | Salzgitter AG
[17] Sidenor acquires the scrap company Miguel Martín - Sidenor

6 Steel and metals action plan and retaining steel scrap

The Steel metal action plan explicitly recognizes steel scrap as a strategic secondary raw material for achieving circularity and decarbonization EU objectives (European Commission, 2025). The plan is structured around six themes, one of which is dedicated to "promoting circularity for metals" and it proposes a range of measures to stimulate domestic demand for scrap, improve sorting and treatment processes, and incentivize investments from both recyclers and end-users. Reducing steel scrap "leakage" is one of the key priorities identified in this action plan. The European Commission is currently considering trade measures to stimulate demand within the EU. To illustrate, the commission will determine whether additional (under the Circular Economy Act) measures, such as export fees or export restrictions, are necessary to boost the availability of steel scrap by increasing the price for third countries to access such materials. The steel and metals action plan's potential measures for the steel scrap trade have brought mixed visions from the EU recyclers' and steel producers' sides.

European steel producers, represented by associations like EUROFER, view these exports as a "leakage" of a strategic raw material. They argue that this scrap should be retained and utilized within the EU to support decarbonization efforts, reduce reliance on imported primary raw materials, and enhance strategic autonomy[18]. Steel producers have also raised concerns that some receiving countries of steel scrap may have less stringent environmental standards and potentially subsidize their recycling capacities, leading to unfair competition and undermining the EU's own sustainability and climate goals. On the other hand, steel scrap companies oppose further export restrictions, suggesting that exports occur primarily because of insufficient domestic demand or a lack of capacity within the EU to process all the available scrap, particularly lower-quality grades. Steel scrap companies suggest that additional restrictions could affect the domestic prices of steel scrap, deteriorating the economic viability of this industry.

Retaining steel scrap rather than exporting it could enhance the overall capacity utilization of domestic steel production. To illustrate, an 80% overall capacity utilization translates approximately to 85 million tons (BOF route) and 69 million tons (EAF route) produced annually. Considering an average 22% scrap input (considering process losses) for the BOF[19] route and 113% (considering process losses) for the EAF route (Remus et al., 2013)[20], 97 million tons of steel scrap input would be required on an annual basis to operate the EU steel

[18] https://www.argusmedia.com/en/news-and-insights/latest-market-news/2627874-eu-steelmakers-ask-for-scrap-export-curbs
[19] BOF EU routes often use 15% to 30% (limit) of steel scrap as input to be mixed with the hot metal given the inflexibility of this process to remove impurities and to not risk the stability (temperature-wise) of the entire operations, leading to a share of relatively clean steel scrap market taken also for these operations.
[20] Calculation are based on table 7.3 Input/output data from 21 existing basic oxygen steelmaking plants in different EU member states and table 8.1 Input/output data for electric arc furnaces within the EU.

industry at 80% of capacity utilization. This steel scrap requirement stands right below the average (in the last ten years) 95 million tons of steel scrap collected annually in the EU (without considering imports and exports). However, this is under the assumption that all collected steel scrap is of adequate quality. The availability of high-quality scrap is a critical constraint (Boldrini et al., 2024). Most of the steel scrap exported from the EU is of mixed quality, often containing varying levels of impurities (which increase over time), such as copper and tin (Celada-Casero et al., 2023). It is estimated that 70% of the scrap exported from the EU is of lower quality[21]. Note that steel scrap dynamics is only one of several other parameters related to the steel production market. Despite suggesting that enough material (depending on quality) can be collected internally to increase the capacity utilization of the steel industry, steel production also relies on other relevant drivers such as international competition, steel demand and energy prices.

[21] https://www.steelorbis.com/steel-news/latest-news/international-environment-council-at-bir-data-driven-facts-will-support-recycling-industrys-efforts-1394516.html

7 Steel scrap quality

"Tramp elements" in steel are dissolved elements, like copper, tin, nickel, and molybdenum, that are unintentionally present in steel due to the use of steel scrap metal in the steelmaking process. These "tramp elements" are extremely difficult and costly to remove using conventional steelmaking technologies, given that "tramp elements" are more noble than iron, making oxidation (the primary refining process for BOF and EAF) ineffective (Van der Weijde, 2025). "Tramp elements" can have detrimental effects on the mechanical properties of the new steel, such as increased susceptibility to cracking during casting and rolling (Dworak et al., 2022). Note that EAFs are more similar to a remelting technology/smelter, opposite to BOF, which can be considered more similar to a refining technology. In addition, EAFs' scrap input is generally higher. Therefore, the quality of steel output in EAFs is largely driven by the quality of steel scrap input. This establishes a direct correlation between the quality of steel scrap and the capability of the product. These consequences are the primary technical reason why steelmakers place strict limits on the use of contaminated post-consumer scrap for high-value applications. Steel producers with EAFs need to secure the supply of high-quality steel scrap or use a portion of virgin iron units (generally direct reduced iron – DRI) in their production process to dilute the concentration of tramp elements to an acceptable level. Given the increase in announced EAF projects, the role of steel scrap quality becomes central. This process can lead steel producers to face intense competition for high-quality steel scrap, necessitating the need to invest in DRI processes or produce lower-grade steel types.

For steelmakers, especially those operating EAF routes, low-quality scrap can incur hidden costs reflected in increased energy consumption (Facchini et al., 2021). Non-metallic components of steel scrap, such as oxides, dirt, and other elements (estireles), do not contribute to the final products and need to be melted, leading to higher energy usage and an increased usage of fluxing agents, such as lime and dolomite, to manage impurities from contaminated scrap. These fluxing agents combine with the non-metallic contaminants to form slag. Therefore, slag production is partly related to the quality of the steel scrap. In addition, there is a risk that, due to contamination, the end product fails to meet the customer's specification and potentially sold as a lower-value product.

Given the natural complexity of removing "tramp elements" during the steel production process, it is therefore preferred that such elements be handled and sorted at an earlier stage. Sorting can be a complex process because of the heterogeneity of modern steel scrap, particularly from post-consumer sources like vehicles and electronics. Nevertheless, mechanical sorting plays a key role across the recycling value chain as it physically identifies and separates entire pieces of scrap that are rich in tramp elements before it gets melted down. Note that mechanical sorting does not remove the "tramp elements" present in a piece of steel. Magnetic separation and Eddy current separators are used to separate ferrous from non-ferrous metals and other waste effectively. However, these steps are insufficient for distinguishing between different steel grades. Additional advanced sensors, which have a high capital cost, such as X-ray Fluorescence (XRF) and Laser Induced Breakdown Spectroscopy (LIBS), are used to identify and sort different types of alloys, helping to upgrade stock and distinguish between various steel grades.

After sorting and separating, the most widely adopted method used by EAF steelmakers to manage low-quality steel in their process is to blend it with large quantities of a cleaner iron source, typically virgin iron in the form of DRI or hot metal (molten pig iron) (Celada-Casero et al., 2023). By adding enough "clean" iron, the overall percentage of impurities in the final melt is lowered to a level that meets the product specification. However, this can be more costly, as it requires the purchase of "clean" iron and also results in higher amounts of slag to be managed. There are some emerging and experimental chemical processes available to reduce impurities in steel scrap, such as sulfide based flux processes, selective chlorination, and non-ferrous metal baths (Gao et al., 2021). Still, these options are viable for a few coating elements and present significant challenges in terms of cost, energy usage, and potential cross-contamination.

8 Steel scrap in the Netherlands

8.1 Use side

Tata Steel is the only steel producer in the Netherlands with their BOF process in IJmuiden. Tata Steel production is tailored to high-grade steel types for a wide range of end uses[22]. Tata Steel primarily uses virgin iron ore and molten iron from a blast furnace as its main feedstock, as it is a "clean", consistent, and predictable feedstock with low levels of impurities. This high level of purity enables Tata to exert precise control over the final chemical composition by adding specific amounts of alloys to produce high-specification steels and high-quality products.
The use of steel scrap for Tata has remained relatively constant over time, with the exception of a small reduction from the 2015/2016 production year (see Figure 6). On average, the IJmuiden facility uses 15-20% of steel scrap as input for its crude steel production, with approximately half of it being sourced externally[23]. By 2030, Tata Steel is aiming to increase its total steel scrap input to 30%, compared to 17-20% in the most recent years, and include an EAF (<= 40% steel scrap input) and DRI plant. This would mean that Tata Steel would need to source an additional (approximately) 760,000 tons of high quality steel scrap annually (compared to 610,000 tons sourced on average from external sources in the last 5 years) to meet such objectives under the current production pathways and average crude steel production values from the last years. However, Tata has no further plans to introduce further amounts of steel scrap usage in the near future, as this will lead to major challenges in delivering the high-quality grades of steel and products that are their market focus.

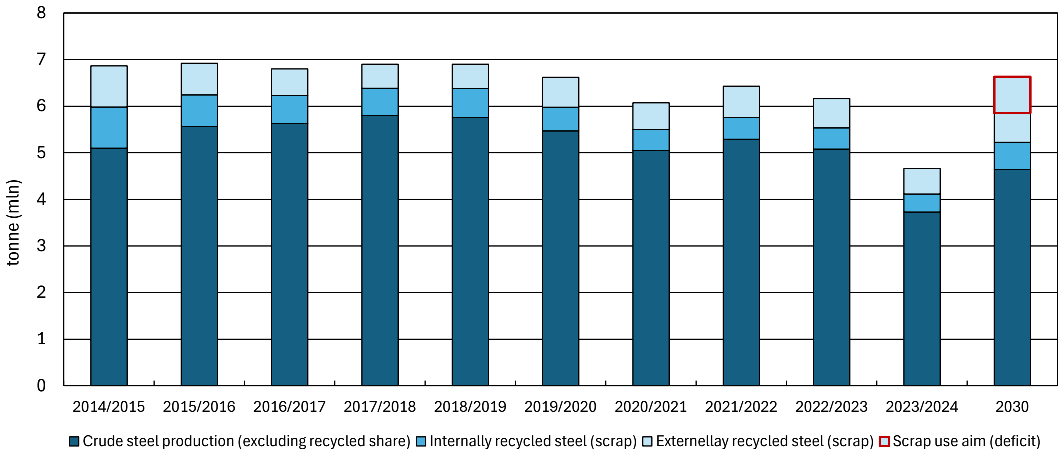

Figure 6 Tata Steel IJmuiden crude steel production and steel scrap use over time. Data based on Tata Steel sustainability reports

[22] Applications of steel | Tata Steel
[23] Sustainability report | Tata Steel

8.2 Supply side (focus on ferro-metals)

The metal recycling sector in the Netherlands processes significant volumes of steel scrap for domestic and mainly international markets. The industry utilizes deep-sea port access for export and employs various technologies for quality control. Key companies include European Metal recycling (EMR group), Jansen Recycling Group, HKS and Jewometaal Stainless Processing B.V, which collectively process over 2.5 million tons of scrap metal annually. The Metal Recycling Federatie (MRF) functions as the industry's representative organization, acting as a point of contact for government and commercial entities. The MRF represents the interests of more than 140 members who are responsible for 85% of the metal recycling turnover in the Netherlands. The MRF is the point of contact for governments, chain partners and regulators.

EMR handles approximately 1 million tons of material annually in its Rotterdam facility[24], with a focus on ferrous scrap. EMR operates two deep-sea export terminals in Amsterdam and Rotterdam for ferrous scrap. The Amsterdam terminal supplies Tata Steel. The group operates two yards that process both ferrous and non-ferrous metals in Alphen aan den Rijn and Nijmegen. HKS (a subsidiary of Remondis) processes annually over 1.5 million tons of ferro metals and is directly involved in demolition projects[25]. The company operates numerous sites across the Netherlands, including locations in Amsterdam, Moerdijk, and Nijmegen. Jansen Recycling Group processes 350,000 to 450,000 tons of scrap annually at its facility in Dordrecht[26]. Jewometaal is a subsidiary of ELG GmbH and processes 250,000 tons of stainless steel scrap annually, with its operations located in the PoR[27]. These companies already include high-quality control processes and apply mechanical sorting technologies, such as based on spectrometric technologies like XRF and LIBS.

Other facilities recover or handle ferrous and non-ferrous metals from different sources, such as NRC, which focuses on the recovery of metals from bottom ash[28]. However, these types of facilities currently fall outside the scope of this case study.

[24] Sustainability in metal recycling: Cooperation EMR and SENNEBOGEN
[25] HKS - The Metal Company
[26] Over ons | Jansen Group
[27] Locations | ELG Germany
[28] bottom ash processing | How does bottom ash processing work? | NRC

9 Steel scrap as a source of CRMs

Steel scrap can be a source of CRMs as well as other strategic metals listed in the CRM Act. Figure 7 represents the elemental composition of the steel scrap trade balance for the Netherlands. From the element present in steel scrap according to (Cai et al., 2023)[29] manganese (Mn), nickel (Ni), and copper (Cu) are considered critical and strategic; aluminum (Al- merged recently by the commission with bauxite), vanadium (V) and niobium (Nb) are considered critical; while iron (Fe) tin (Sn), led (Pb) chromium (Cr) molybdenum (Mo) and zinc (Zn) are also present but not listed in the CRM act. Other CRMs may also be present in steel scrap, but insufficient information was available. By mass, steel scrap (and steel) can be a host to a large amount of CRMs when compared to other end-uses. For example, on average, 1 million tons of manganese (Mn), 0.9 million tons of nickel (Ni), and 0.5 million tons of copper (Cu) present in steel scrap are traded to third countries from the Netherlands (see Figure 7). V and Nb are also traded in relevant amounts. However, the main uses of these elements are related to the steel industry. Over time, the elemental trade balance of steel scrap for the Netherlands has stayed constant except for nickel in 2022, when the trade balance of stainless steel was negative (more imports than exports).
The recovery of CRMs from steel scrap is limited by significant technological and economic challenges, particularly in the case of copper. Due to fundamental thermodynamic constraints, removing copper once it is melted and dissolved in molten steel is not (economically) viable for bulk production (Paeng et al., 2024). The only viable strategy for steelmakers to manage copper contamination is dilution with purer iron, such as DRI or pig iron (mentioned in the steel quality section). Therefore, for CRMs in steel scrap, especially the case of copper (Cu), the most viable strategy remains to prevent copper from entering the furnace in the first place through (advanced mechanical) scrap sorting (Daehn et al., 2019). This is the same case for other alloying CRMs elements such as nickel (Ni).
Besides the thermodynamic and technological challenges, the increasing demand for steel scrap can consequently lead to higher prices for this material and act as a powerful economic incentive that discourages the use of steel scrap as a viable option for recovering individual CRMs for different applications. Nevertheless, a wide price gap between high and low steel scrap quality, in combination with the high value of specific CRMs, may lead to a business model for the recovery of some elements in the future.

[29] The percentage values from each CRM are multiplied by the Dutch trade data to obtains mass values over time

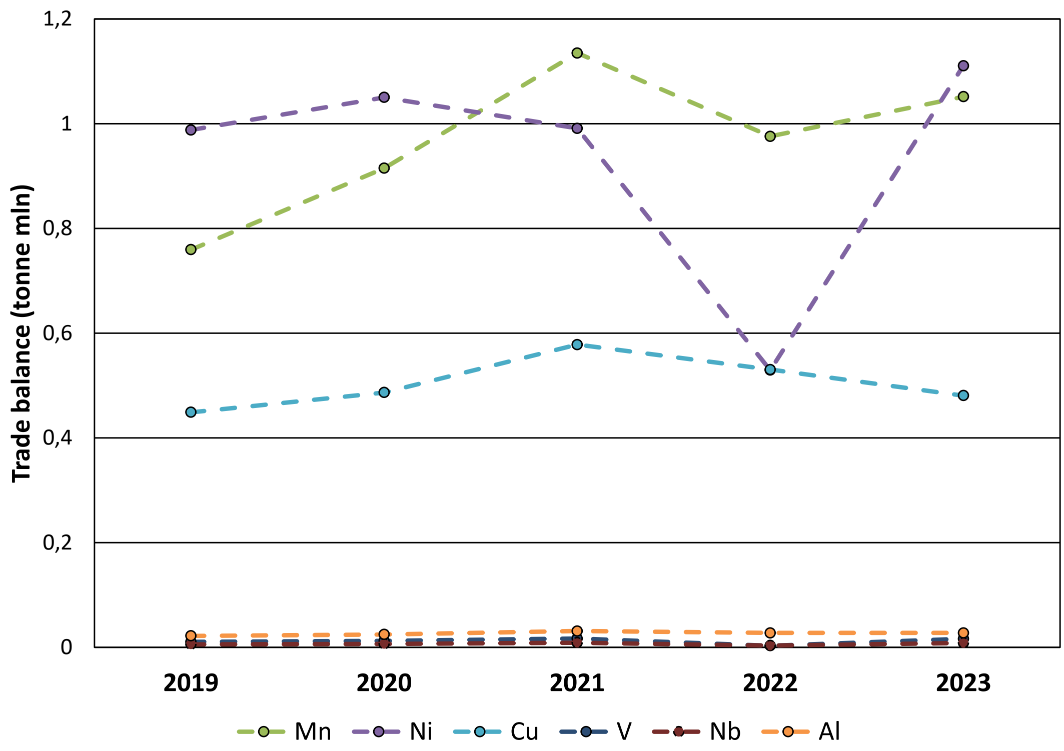

Figure 7 CRMs present in steel scrap trade for the Netherlands.

9.1 CRMS present in alloys imports

For the Netherlands, CRMs are also imported in the form of ferroalloys. These materials typically contain a high concentration of iron and other elements, such as chromium (Cr) or manganese (Mn). The majority of worldwide ferroalloy consumption is in the iron and steel industry (Eric, 2024). Tata Steel is the main user of ferroalloys in the Netherlands and has carried out efforts to map the supply chain of 15 high-risk materials (including ferroalloys)[30]. Of the 15 high-risk materials, 5 are related to ferroalloys, primarily including ferromanganese, ferrochromium, ferroniobium, ferrovanadium, and ferrosilicon. Ferronickel is not included in the Tata high-risk steel list, but it's also used to some extent in certain types of steel production, such as the Hilumin product line related to battery manufacturing[31]. Figure 8 shows the trade balance of the ferroalloys for the Netherlands on an element basis for the CRMs present in those feedstocks. The positive trade balance indicates that the total amount of imports exceeds the total amount of exports, exemplifying the relevance of these CRMs for steel production in the Netherlands. To illustrate, according to World Bank data, the Netherlands is one of the top worldwide importers of ferrosilicon (>55% Si content) and ferrosilicon-manganese (World Integrated Trade Solution, 2024e, 2024h) .
The highest positive trade balance for the Netherlands in the last years on an element level is for silicon (Fe-Si >55% Si content), manganese (Fe-Si-Mn), manganese (Fe-Mn >2%C) and manganese (Fe-Mn <=2%C) to a lower extent (see Figure 8). Manganese (Mn) and silicon (Si) are key elements for steel production. Manganese (Mn) plays a critical role in steel production,

[30] Tata Steel sustainability report 202223.pdf
[31] HILUMIN Electro-plated Steel | Tata Steel Nederland

preventing the steel from becoming brittle and avoiding cracking during the hot rolling or forging process. Manganese (Mn) also helps remove oxygen from the process and, as an alloying element, increases the manganese properties of steel, such as hardness and resistance to corrosion (Olsen et al., 2007). Silicon (Si) is also used as a deoxidization element (even more powerful than manganese - Mn) to ensure material quality. Note that generally, manganese (Mn) and silicon (Si) are used as an effective and economical method to remove oxygen in steel production. Silicon (Si) is also applied as an alloying element, particularly in the manufacturing of steels for electrical applications, as it improves the steel's magnetic properties and electrical resistivity (Elgamli & Anayi, 2023).

Norway and Iceland are strategic partners for the Netherlands in the supply of ferroalloys, and consequently, they are highly relevant for steel production in the country. Norway has been the main source of manganese (on a ferroalloy element level) for the Netherlands. Over the last few years, approximately 60% of Dutch imports for Fe-Mn alloys with a carbon content of < 2% and 56% of Fe-Si-Mn alloys were sourced from Norway, with imports from other countries accounting for comparatively less (World Integrated Trade Solution, 2024a, 2024d). Norway is also responsible for 20% of Dutch Fe-Mn > 2%C import, only surpassed by Latvia (25%)(World Integrated Trade Solution, 2024b). The main source of silicon (Fe-Si >55% Si content) for the Netherlands' steel production is imported mainly from Iceland (47%) and Kazakhstan (20%), to a lesser extent (World Integrated Trade Solution, 2024f). Note that silicon is also sourced and present in the Fe-Si-Mn alloy.

Niobium (Fe-Nb) and vanadium (Fe-V) also present a positive trade balance, but to a considerably lower extent when compared to other ferroalloys. The use of these elements in steel production is more tailored to enhance specific characteristics of steel. Ferroniobium is primarily used in the production of high-strength low-alloy (HSLA) steels. The addition of small amounts of niobium (Nb) significantly refines the grain structure of the steel, enhancing the steel's strength, toughness, and weldability, making it essential for demanding applications (Sun et al., 2022). The primary application of vanadium (V) is as a strengthening agent for steel, enhancing its strength, wear resistance, and high-temperature performance (Yang et al., 2021). It is commonly used in tool steels, high-strength structural steels, and automotive components. The use of vanadium (V) and niobium (Nb) in Tata Steel IJmuiden is connected to their Ympress HSLA and Valast steel product lines[32].

Brazil accounts for 90% percent of worldwide ferroniobium (Fe-Nb) production (SCRREEN, 2020a). The majority of niobium (Fe-Nb) imports to the Netherlands are sourced from Brazil (World Integrated Trade Solution, 2024c), indicating the significance of this high strategic partnership that enables the production of high-quality steels in the Netherlands. Ferrovanadium (Fe-V) imports are primarily sourced from Austria (60%), South Africa (17%), and China (7%) (World Integrated Trade Solution, 2024g). Only Austria and the Czech Republic produce ferrovanadium (Fe-v) in the EU.

[32] Valast abrasion resistant steel | Tata Steel - Ympress® | Tata Steel in Europe

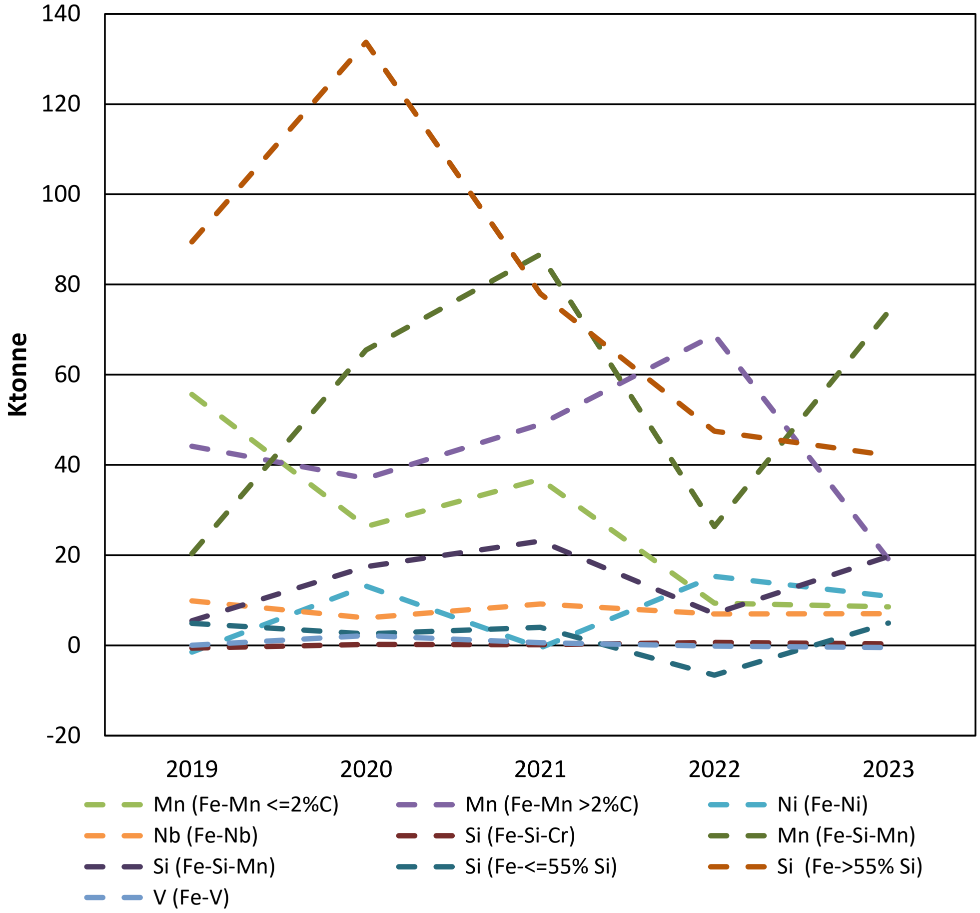

Figure 8 CRMs present for selected ferroalloys trade balance in the Netherlands[33]

9.2 General content of minor alloying CRMs (elements) in steel and recycling potential

Steel is the world's most recycled material, but its recycling loop primarily focuses on recovering iron, rather than other elements (Schlegel, 2023). As previously mentioned, steel (and steel scrap) is a host for a wide array of elements that serve as alloying agents or residual "tramp" elements.
Alloying elements provide a specific function based on the functionality of a steel type and the amount of each element present in that steel type is precise. For example, the average content of vanadium (V), niobium (Nb), and titanium (Ti) in different product series from Tata Steel is lower than 0.1% on a mass percentage basis (see Figure 9). To illustrate, for the Valast series (abrasion-resistant steel), the niobium (Nb) content is 0.06%, which means that for

[33] The elemental content of each ferroalloy is established by multiplying the trade balance in mass by the average element content specified in the technical delivery requirements ISO guidelines of each ferroalloy. ISO 6501:2020 – Ferronickel; ISO 5445:1980 – Ferrosilicon; ISO 5453:1980 – Ferroniobium; ISO 5451:2022 – Ferrovanadium; ISO 5446:1980 – Ferromanganese; ISO 5447:1980 – Ferrosilicomanganese; ISO 5449: 1980 - Ferrosilicochromium

each ton of Valast series steel, 0.6 kg corresponds to niobium (Nb). Given the high-quality specifications of such steel types, high-quality steel scrap with a known chemical composition can be used as input to maintain the same steel type specification and ensure its performance. Therefore, steel producers prefer a closed-loop recycling in which the share of steel scrap used as input (round-around scrap or pre-consumer scrap) preserves the functions of the alloying elements and maintains their value. This component is crucial for producing high-quality steel.

Post-consumer steel scrap is collected from various sources and products with different steel grades. It is considerably technically and economically challenging to sort the varied stream of steel scrap according to its alloy compositions. Therefore, most steel scrap is mixed and shredded and sold in bulk (Panasiuk et al., 2022). The consequence of using this mix (especially EAF routes – open-loop recycling) is that the resulting liquid metal has a diluted, intermediate chemistry, in which the valuable alloys are spread across the entire batch (Harvey, 2021). At this processing stage, it is technically and economically extremely challenging to extract the different CRMs. The new chemical composition lacks the specific standards of high-quality steel types, making it unsuitable for such applications. Therefore, this downgraded steel now becomes a product such as rebar with low technical requirements that can tolerate this mixed chemistry. Hence, the high-value functions of alloys have been permanently lost through dilution and have become residual or "tramps" elements in the composition. Note that high-grade steel products cannot be made from this downcycled material; thus, steel producers will continue to rely on primary raw materials (iron ore and ferroalloys from mining) to create such products.'

While it is challenging to approximate the theoretical potential of CRMs available in steel scrap, an approximation can be established for copper, as it is the main "tramp" element and thus more information is available. Based on Daehn et al. (2019), an approximation of the copper (Cu) content in steel scrap, ranging between 0.15% and 0.45%, can be used to estimate such values. The lower end (0.15%) represents a market mix with a higher share of clean, well-sorted, and specified scrap. The higher end (0.45%) reflects a mix with more high-copper-content materials, such as End-of-Life Vehicles (ELVs) and other unsorted consumer goods. Note that the EU steel scrap market is not uniform; it is a complex mix of different scrap types and grades, each with its copper (Cu) concentration. Therefore, a single value is not accurate. With an average (in the last ten years) of 94.5 million tons per year of steel scrap collected in the EU, an estimated 142 to 425 thousand tons of copper (Cu) per year can be present as residual elements in this feedstock pool. This copper feedstock pool is equivalent to 5% to 16% of the EU's total refined copper production[34].

Given the high volume of steel production and steel nearing the end of its life worldwide, it can act as a significant carrier of CRMs. While this offers a theoretical "urban mine" of materials, the fact is that current production practices associated with different steel qualities, steel scrap processing systems, recycling targeting iron, and technical and economic drivers lead to a systemic dissipation and functional loss of alloying elements. Therefore, the potential contribution to recovering CRMs from steel scrap requires overcoming technical, financial, and processing challenges associated with steel production, in addition to significantly improving and shifting to steel scrap sorting based on alloy content.

[34] Average of 2.6 million tonne refine copper production in recent years for the EU RMIS - Raw materials' profiles

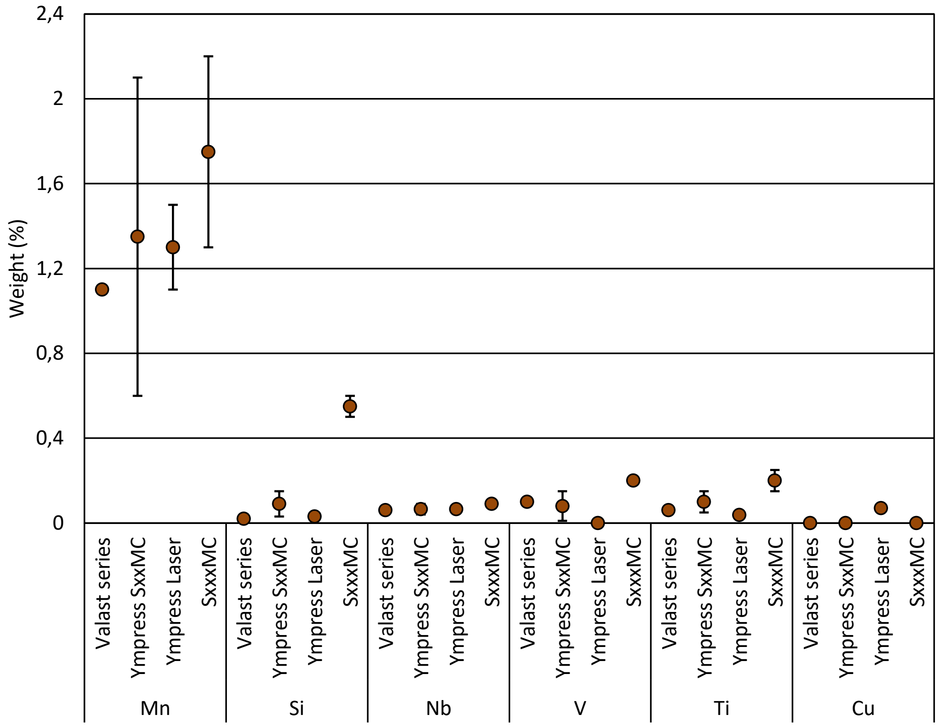

Figure 9 CRMs content present in different Tata Steel product series[35]. The ranges indicate the maximum or minimum content of a specific material composition within that product series. Average element content values across series products are used for display purposes.

[35] Valast abrasion resistant steel | Tata Steel - Ympress® | Tata Steel in Europe

10 The potential effects of USA tariffs on steel scrap EU market

US tariffs on steel imports can have consequences for the EUs steel scrap market as a result of the interconnected roles of different market actors and countries. The US steel industry produces approximately 70-71% of its steel using steel scrap dependable EAFs[36]. While its domestic consumption is high, the US is also the world's largest exporter of scrap, shipping approximately 15-17 million tons annually[37], with Turkey being its primary destination (4.5 million tons approximately). As mentioned earlier, the EU and the Netherlands are also major steel scrap exporters to Turkey. Turkey is the largest steel scrap importer in the world, bringing in over 20 million tons in 2024 to sustain its EAF-heavy industry, with the US and EU nations being its most crucial suppliers.

The introduction of US tariffs on steel could act as a catalyst within these pre-existing challenging market dynamics. The tariffs would incentivize US steel producers to increase domestic production to replace more expensive imports. This increased output from US EAF steel producers will require more domestic scrap, directly reducing the volume available for its export market. A material reduction in US exports would decrease the global supply of scrap. For the EU, the consequences can be direct. It can derive in upward price pressure on a key industrial input. For context, Turkish import prices are a key global benchmark, and a supply shock from its top supplier, the US (which provided approximately 4.5 million tons to Turkey in 2024)[29], would force it to seek replacement of feedstock more aggressively from other regions, including the EU. This can lead to increased competition for the pool of available material, affecting raw material costs for EU steelmakers who currently have an EAF route and are looking to increase capacity with this route. This demonstrates how a targeted trade policy can alter global commodity flows, directly impacting the cost structures and strategic viability of the industrial and environmental policies of other nations.

[36] New Study: Enough Scrap to Meet Rising U.S. Demand for Recycled Steel - Steel Manufacturers Association
[37] US scrap exports decline for third consecutive year

11 Discussions and recommendations

Dutch perspective

For the Netherlands, steel scrap consumption is expected to increase as Tata Steel IJmuiden plans to increase scrap steel input from 17% to 30%. This increase in demand will be specifically for high-quality steel scrap required to produce the specific categories of steel at this facility. Tata will rely on high-quality steel scrap imports to achieve these objectives, given the potential domestic shortage of this feedstock type.

Currently, the PoR is a major export hub for ferrous scrap. Key companies leverage strategic deep-sea port locations, such as Rotterdam and Amsterdam, along with advanced sorting and processing technologies, to supply large amounts of ferrous and non-ferrous scrap to global markets. If the EU stimulates the demand internally by implementing additional export restrictions, the flow of scrap through Rotterdam to non-EU countries can be reduced. This process can lead to economic challenges for logistics and trading companies that have built their business case around these exports.

EU perspective

The expected increase in demand for high-quality steel scrap presents an opportunity to invest in and research advanced upgrading and processing technologies to meet the potential high-quality feedstock demand of Tata Steel IJmuiden and other European facilities. Governments can lower this barrier through targeted financial incentives for innovations and mechanical separation. This funding can target innovation for scalable and economically viable techniques to remove contaminants before the melting process, as this remains a significant technological gap. For example, focusing on avoiding the downgrading (contamination with other elements, such as copper, in the shredding process) of steel scrap, as it ultimately leads to lower-quality steel and loss of elements to dilution. This outcome can also contribute to the EU's strategic autonomy and decarbonization strategy, especially for EU countries that rely heavily on EAFs for their steel industry.

Policy can facilitate the establishment of long-term domestic partnerships between steel producers and steel scrap processors, thereby creating the necessary conditions for technological investment and innovation. This approach needs to acknowledge the different market dynamics that can arise from a globally traded product and establish mechanisms to mitigate potentially higher spot prices. Note that global trends influence steel scrap prices in steel scrap, iron ore, and finished steel, which will continue to be shaped by international demand and geopolitical events. In addition, the competitiveness of Dutch steel will be directly tied to the availability of affordable (low-carbon) electricity.

Steel scrap and CRMs

Steel scrap is a host for strategic CRMs such as copper (Cu), nickel (Ni), niobium (Nb) and vanadium (V). Although steel scrap recycling offers the theoretical potential to recover valuable Critical Raw Materials (CRMs) and precious metals in addition to iron, the high cost, technical and thermodynamic challenges of current extraction methods (energy-intensive or chemical processes) often make it unviable. Furthermore, the volume of certain elements present in the current steel scrap stream, along with the logistics surrounding it, makes it challenging to justify large-scale dedicated recycling facilities for embedded CRMs. There are significant technological challenges associated with separating alloys and removing impurities, particularly copper (Cu). Nevertheless, if more advanced separation techniques are adopted across the EU to avoid the downcycling of steel scrap and isolate efficiently the material streams with a high level of impurities, in that case, this can create the starting point to investigate further the economic and technological feasibility of developing processes for the recovery of secondary materials once enough volumes are available. This can also help to understand and shape the potential contribution of lower-quality steel scrap as a source of CRMs for the EU's ambitious recycling targets.

<u>Exports of steel scrap</u>
The 'scrap leakage' discussion is directly linked to the context of the EU's strategic autonomy and green steel transition. A complex market scenario can arise if the EU increases its use of Electric Arc Furnace (EAF) steelmaking, which relies on steel scrap, without concurrently developing policies for scrap quality and managing energy prices for EAFs. Demand for high-quality scrap could increase, potentially driving up its price. On the other hand, lower-quality scrap might continue to face export pressures or experience low domestic prices if offtake mechanisms are insufficient (currently, the ban on exports to non-OECD countries). This situation could create economic challenges for smaller recyclers and lead to increased EU import dependency for high-quality scrap (if available, as other countries will probably use the high-quality scrap themselves) if domestic upgrading capacity (ranging from low to high quality scrap) does not scale to meet demand.
These drivers also present an opportunity for the EU internal market to face its quality problem. With a more limited export market for low-grade material, producers and recyclers can have an economic incentive to invest in (advanced) mechanical separation processes with the support of policy incentives, avoid downcycling of steel scrap to a certain extent and increase the use of this feedstock locally.
Addressing these challenges also requires a strategy that extends beyond the promotion of EAF technologies and should focus on:

- Ensure competitive energy prices for the industry
- Development of off-take mechanisms for different scrap qualities.

12 The role of steel scrap in the context of the CRMA

Steel scrap is one of the most significant pools of CRMs in Europe. However, more research is required to understand the full potential of recycling individual elements from steel scrap and their contribution to the CRMA benchmark. Note that in principle, the CRMA's 25% recycling benchmark focuses on increasing the EU's capacity to produce distinct, usable secondary raw materials (elements) from waste, and steel scrap is generally characterized as a secondary material. Furthermore, given that several elements present in steel, such as vanadium (V), niobium (Nb), and nickel (Ni), are primarily consumed in the steel industry, conceptually, it is counterproductive to separate these elements as long as the primary uses of these elements remain in the steel production loop. Therefore, the hypothetical contribution of these individual elements to the CRMA recycling benchmarks can be negligible. For other elements, such as copper (Cu), there can potentially be a contribution to the recycling benchmarks to some extent. Nevertheless, this is conditioned on the improvement of sorting processes, overcoming technological challenges to separate these elements from steel (as mentioned before), policy support towards innovation, and the generation of business opportunities to recover these elements for other end uses. Having such a system in place can be a lengthy process, resulting in the contribution of these elements becoming minimal for the time horizon under the CRMA.

Supplementary material

Table SM 1 Share of Dutch exports in the global export market.

	2019	2020	2021	2022	2023
Ferrous products: remelting scrap ingots	1,0	2,5	2,7	3,4	4,9
Ferrous waste and scrap: n.e.c. in heading no. 7204	5,1	5,6	6,2	6,2	6,0
Ferrous waste and scrap: of alloy steel (excluding stainless)	2,2	2,6	2,6	1,7	3,2
Ferrous waste and scrap: of cast iron	2,2	4,5	2,5	2,8	3,8
Ferrous waste and scrap: of stainless steel	10,5	10,0	8,4	8,1	9,3
Ferrous waste and scrap: of tinned iron or steel	2,8	2,4	1,9	2,5	2,4
Ferrous waste and scrap: turnings, shavings, chips ...	5,5	5,2	6,6	5,8	4,5

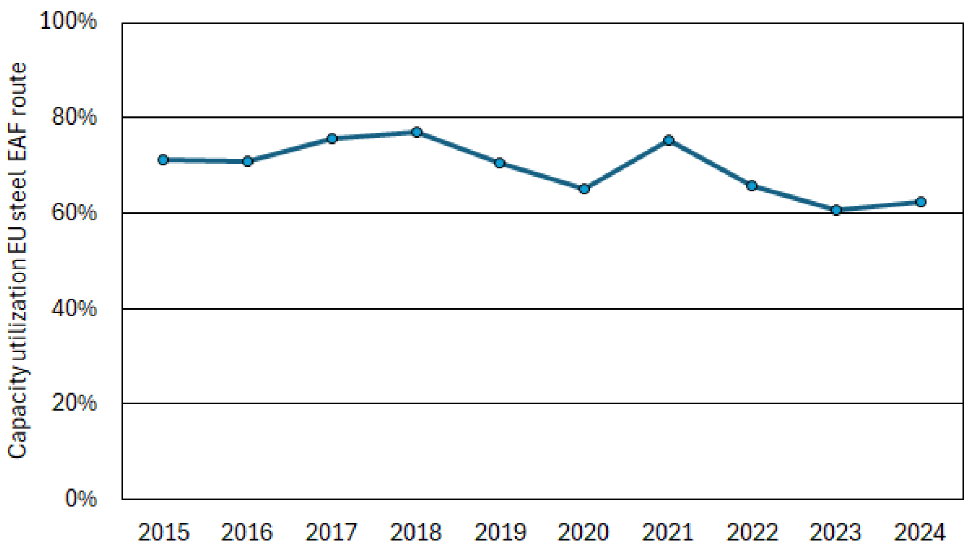

Figure SM 1 Capacity utilization of EU steel production over time for the EAF route.

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