

1 Reduction of Greenhouse Gas Emissions in the Life Cycle of Steel

In this appendix, a simplified overview of the steel product life cycle is provided, including examples of how and where greenhouse gas emissions can be reduced. The area has been described from a technical perspective, and any political uncertainties have not been taken into account. Initially, steel production is discussed in general, followed by methods to reduce climate emissions in the steel life cycle and an assessment of what will happen in the near future. Alloys constitute a separate area and are addressed in a dedicated chapter at the end. The presentation is intended for those who, for various reasons, are interested in climate efforts in the steel industry but have not studied steel production in detail. Comments are welcome and can be sent to rutger.gyllenram@kobilde.com.

1.1 The life cycle of Steel - Basics

Steel: Steel is an alloy of iron (Fe) and carbon (C) with a carbon content ranging from very low values up to 2%. At higher carbon levels, the alloy is called cast iron. Steel is alloyed with other metals such as manganese (Mn), silicon (Si), chromium (Cr), nickel (Ni), molybdenum (Mo), tungsten (W), vanadium (V), niobium (Nb), and antimony (Sb). Depending on the alloy content, steel can have either a ferritic or austenitic crystal structure. Ferritic steels are magnetic, while austenitic steels are non-magnetic. A steel product is manufactured according to a specification that determines ranges for various alloying elements and maximum levels for contaminants/trace elements that are not desired in the steel. Common contaminants include copper (Cu), tin (Sn), lead (Pb), and phosphorus (P). Valuable alloying elements such as chromium, nickel, and molybdenum can also be considered contaminants in certain types of steel.

Iron Ore: Iron naturally exists mainly in the form of iron oxide, a compound of iron and oxygen (O), or iron hydroxide, which also contains hydrogen (H). The iron ore is accompanied by gangue, a mix of other substances such as compounds of silicon, aluminum (Al), calcium (Ca), potassium (K), phosphorus, and sulfur (S). If the gangue is in separate grains, the ore can be processed to achieve higher iron content and purity. Iron-bearing minerals suitable for mining are called iron ores. Iron ore is traded as sinter fines, pellet concentrate, pellets, and, to a lesser extent, as lump ore.

Iron and Steel Scrap: Ferrous waste with a high content of metallic iron is called scrap. Scrap can come from steel mills (internal scrap or revert), from workshops (workshop scrap), or from society after a product has been used and collected (collection scrap).

Ores for Alloying Metals: Alloying elements are also derived from minerals, but these ores often have very low concentrations and are typically more complex.

Coal and Coke: Coal is compressed fossilized plant residues containing a high proportion of the element carbon and is classified based on ash content, ash analysis, and volatile matter content. Coal is ground and dried to form injection coal or dry-distilled in coke plants to produce coke. Other coal products include graphite electrodes, Söderberg electrodes, and calcining coke.

Production of Liquid Pig Iron: In the blast furnace process, layers of iron ore, such as sinter, pellets, or lump ore, along with slag formers, are charged alternately with layers of coke into a tall shaft furnace, the blast furnace. In the lower part of the furnace, hot blast air is blown in along with injection coal and steam. In simplified terms, the oxygen and steam react with carbon and coke to form carbon monoxide (CO) and hydrogen (H₂), which in turn react (reduce) iron oxide to iron and carbon dioxide (CO₂) and water vapor (H₂O). In the upper part of the furnace, the reaction occurs in the solid phase, while in the lower part, an excess of heat causes the ore to melt into a liquid phase.

Blast furnace iron has a temperature around 1500°C, with C=4.2% and Si=0.5%. Slag formers and gangue, in addition to the silicon in pig iron, form a slag that can be used as a substitute for clinker in cement production. Permeability in the furnace is crucial for the process's functioning, and it is ensured by the thickness of the coke layers and the shape of the melt zone in the furnace. Alternative methods to produce liquid pig iron have been developed for over a hundred years, mainly to use fine-grained coal and ore without the need for coke, pellets, or sinter and to utilize electricity for heating. However, the blast furnace process, with its high productivity and energy efficiency, remains the dominant method for producing pig iron.

Production of Sponge Iron: Reduction of iron ore in the solid phase can occur with natural gas, primarily composed of methane (CH₄), or with solid carbon. Natural gas-based processes dominate, and in these, natural gas is preheated and reformed, i.e., cracked, into a so-called syngas, which is a mixture of CO and H₂. Iron ore is reduced similarly to the blast furnace process but does not melt. Methane and process gas are blown into the bottom of the furnace, where sponge iron is cooled and absorbs carbon. Not all iron oxide is reduced, and a metalization level of 92–94% and a carbon content of 2–4% can be considered benchmarks. The idea is that the carbon content should be sufficient to finally reduce the sponge iron. In rotary kiln processes or the Swedish Högånäs process, solid carbon is used as a reducing agent. Sponge iron can be used directly, referred to as DRI (Direct Reduced Iron), or briquetted for further transport, referred to as HBI (Hot Briquetted Iron).

Steel Production from Pig Iron in Converter: In the converter process, oxygen gas (O₂) is blown forcefully into a bath of pig iron, scrap, and slag formers. Oxygen reacts with carbon and silicon in pig iron, forming carbon monoxide, silicon dioxide, and heat, which requires the addition of a coolant in the form of scrap or sponge iron to prevent overheating. The addition of scrap depends on the amount of heat generated, and the addition of slag formers depends on the silicon content in pig iron. Blowing continues until the desired final carbon content is reached.

Steel Production in Electric Arc Furnace: In an electric arc furnace, either scrap or a combination of scrap and sponge iron, along with slag formers, is charged. Energy for melting the material is supplied via graphite electrodes forming arcs against the scrap or DRI, burners with natural gas, propane, or oil in the upper part of the furnace, and by injecting coal and oxygen into the bath to create a foamy slag. The addition of slag formers depends primarily on the silicon content in scrap and DRI, similar to the converter. Blowing continues until the desired final carbon content is reached. It is also possible to operate the electric arc furnace without foamy slag under reducing conditions, reducing losses of alloying elements to slag but placing higher demands on the purity of raw materials.

Secondary Metallurgy and Casting: Steel is tapped at around 1600°C from the converter or electric arc furnace into a movable vessel, called a ladle, for further treatment such as deoxidation, alloying, heating, etc., depending on the steel grade and plant layout. Ladles are preheated before use with natural gas, propane, or oil. Once the steel has the right temperature and composition, it is typically cast in a continuous casting plant or, for certain special steels, in so-called ingot molds to form ingots.

Rolling and Heat Treatment with Multiple Operations: Ingots and continuously cast products are heated to temperatures around 1200°C before being rolled in one or multiple steps, heat-treated at lower temperatures, surface-treated, shaped, and prepared for delivery. Normally, oil, propane, and natural gas are used as fuel, but in some cases, electric furnaces may be used. Examples of heating with hydrogen or biogas exist.

Manufacturing of the Final Product: During the final production of end products containing steel, the material is processed, and some parts become workshop scrap (cut-offs, turning shavings, punch residues, etc.).

Product Usage: The technical lifespan of a product depends to some extent on the choice of materials. Steel with higher alloy content and well-adapted heat and surface treatments can significantly increase durability. Depending on the design, a product can be reused after reaching the end of its use in one application. An example of this is construction materials that are inspected and prepared for reuse in a new building when the old building is renovated or demolished.

Collection and Processing of Scrap: Scrap is categorized into classes based on various classification systems depending on origin and chemical analysis. Complex products like cars and appliances are fragmented, and the pieces are sorted into a magnetic and a non-magnetic fraction. The non-magnetic fraction consists of austenitic, corrosion-resistant steels, copper, and aluminum alloys. In magnetic, i.e., ferritic, scrap from fragmented complex products, non-magnetic metals may accompany, such as copper wire from coils in electric motors. In the ferritic scrap, there is ferritic stainless steel with a high chromium content and special steels like tool steels, bearing steels, and spring steels with percentages of chromium, nickel, molybdenum, and other alloys around one percent.

1.2 Methods to reduce the emission of greenhouse gases in the steel life cycle

1.2.1 Improvement Areas

Emissions of greenhouse gases can be reduced throughout the entire product life cycle, even though achieving zero emissions is challenging today. Some changes can be implemented immediately, while other projects require technological development, which takes time. Changes can be categorized into four main groups, as illustrated in [Figure 1](#). This figure is by no means exhaustive but provides examples of possible changes to reduce greenhouse gas emissions.

Something that should be emphasized at this stage is the unique role of steel during the product's use. Properties such as weight, wear resistance, and corrosion resistance can determine both the amount of steel for an application, the product's lifespan, and functionality, thereby influencing the overall environmental impact of the product over its lifetime. Research for improved material properties, therefore, holds clear climate value.

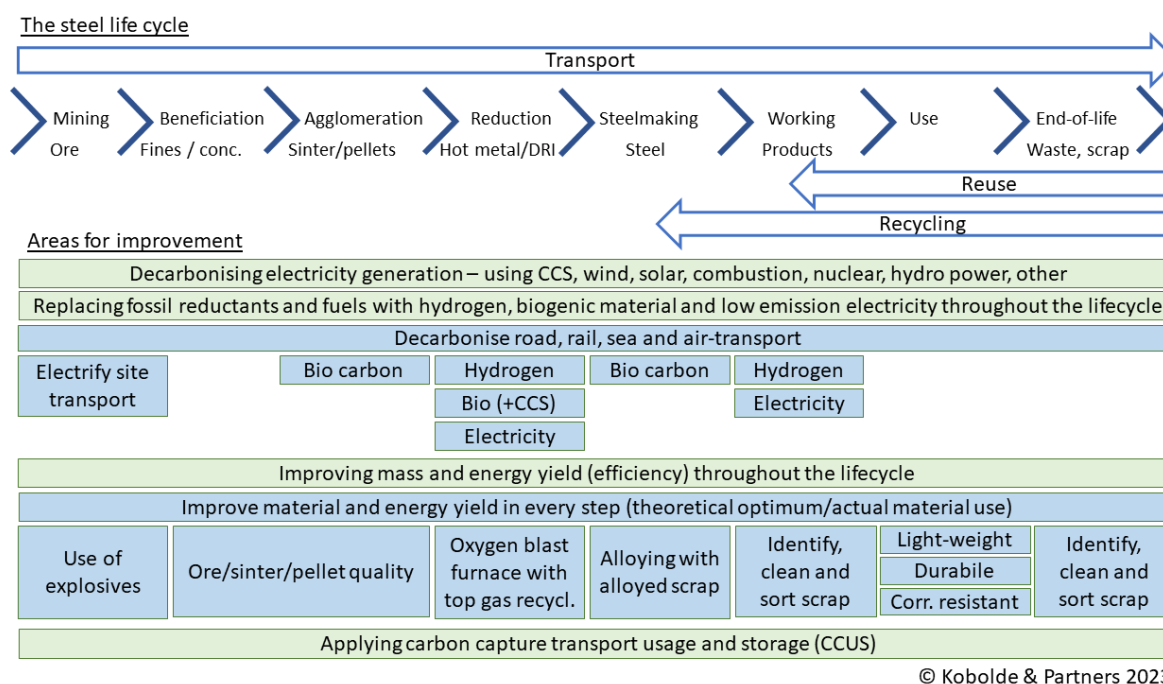


Figure 1. Areas for improvement in the life cycle of steel to reduce greenhouse gas emissions, divided into four main areas with examples of possible measures.

1.2.2 Production of electricity with low emissions

The significance of the electricity mix: Fossil fuels have been utilized for an extended period and currently exhibit high efficiency, meaning they have a high energy yield. However, when transforming fossil fuels into electricity, there are energy losses in the conversion process. If this electricity is then used to produce hydrogen as a replacement for fossil fuels, additional losses occur. Therefore, replacing the blast furnace's iron production with hydrogen instead of coal and coke, and subsequently melting the sponge iron in an electric furnace, does not result in reduced emissions unless electricity production is essentially fossil-free.

The calculation varies depending on whether emissions are assumed to be equal to (1) the average emissions in the grid mix, (2) the so-called marginal electricity, i.e., the highest emission value in the grid mix, or (3) the emission value of the new capacity built to cover increased electricity demand.

The electrification of industry relies on a substantial expansion of the electricity system with an increased amount of fossil-free power production. The entire system must be able to guarantee the delivery of both energy and capacity based on the industry's needs and do so in a cost-effective manner.

1.2.3 Replace Fossil Fuels and Reducing Agents

Transport with Low Emissions: Transportation of raw materials and finished products includes maritime traffic, train transportation, and truck transportation. Emissions can be reduced through electrification with fossil-free electricity, transition to biofuels, hydrogen, and e-fuels produced from carbon dioxide and fossil-free hydrogen.

Electrification Transition to Biochar in Mining and Mineral Handling: Phasing out diesel in mining has both reduced direct emissions and decreased the need for ventilation in underground mines. The use of biochar can replace fossil fuels in the agglomeration step.

Reducing Agents and Low-Emission Fuels: The main alternatives are electricity, hydrogen, and biogenic materials. The fossil reducing agents of the blast furnace, such as coal and coke, can be partially replaced by biochar, biogas, and hydrogen. However, a certain minimum amount of coke must be present to ensure permeability in the furnace. Direct reduction processes using natural gas in sponge iron production have lower emissions than reduction with coal. These processes can also utilize hydrogen as a reducing gas, produced by splitting water or syngas derived from biomass. An alternative to existing iron ore reduction methods, currently in the experimental stage, is the use of electrolysis to reduce iron ore to iron using electricity.

Biochar Instead of Fossil Coal in Steel Production: Ongoing development is exploring how to use biogenic carbon as injection coal in steel processes, for graphite electrodes in electric arc furnaces, for Söderberg electrodes, and as upcycling coal. Investigations are also underway regarding fossil-free casting powder.

Hydrogen, Oxygen, and Electricity in Rolling Mill Furnaces: Over the past decades, oil has been extensively replaced by natural gas and liquefied petroleum gas (LPG). The next step is transitioning to heating with hydrogen produced through electrolysis. By burning fuel with oxygen instead of air, energy efficiency is increased since nitrogen does not need to be heated. An alternative that has been available for a long time is the induction heating of steel materials.

1.2.4 Increasing Energy and Material Yields

Increase Material and Energy Efficiency at Every Stage: By increasing efficiency at every stage of the steel product life cycle, resource consumption and greenhouse gas emissions can be reduced. In principle, all processes can enhance energy and material utilization, but this may require additional research, development, and investment.

Optimization of Explosives in Mining: Emissions from explosives are a source of pollution in the mining industry that can be reduced through optimization.

Optimization Ore Properties: The amount of gangue in ore products like sinter and pellets affects yields, slag former consumption, and energy in subsequent stages.

Oxygen Blast Furnace: The blast furnace process is the dominant smelting reduction process, and numerous projects aim to replace it. An example of process development tested in Sweden is replacing blast air with oxygen. This eliminates the need to heat up the nitrogen in the air, significantly increasing energy efficiency when combined with carbon dioxide separation and recirculation of carbon monoxide in the top gas. This is seen as an opportunity in countries lacking fossil-free electricity, biomass, or natural gas.

Utilize Alloys in Scrap: Another crucial area is improved recycling of alloys from scrap, requiring investments in facilities for processing and sorting scrap, logistics, information transfer, and agreements on cost distribution among product companies/consumers, recyclers, and steel companies. The significance of alloys is described in more detail in section 1.

Yields During the Product's Lifetime: Rarely mentioned is that with high-strength steel, which provides low product weight, as well as durable and corrosion-resistant steel, the need for material decreases. This increases the functionality and lifespan of products containing steel. Thus, a material with higher emissions during production can result in much greater savings during the product's use.

1.2.5 Capture and Usage of CO₂ (CCUS)

Carbon Capture and Usage or Storage (CCUS): This concept involves removing carbon dioxide (CO₂) from the cycle or using it in a product that would otherwise have relied on fossil fuels and resulted in fossil emissions. CCUS is generally economically viable for large point sources, such as a coal-based power plant, a blast furnace, or a direct reduction furnace. Collection is facilitated if the carbon dioxide is free from nitrogen, making CCUS suitable for CO₂ from oxygen blast furnaces and direct reduction furnaces, which have exhaust streams meeting these criteria. If CO₂ from biogenic sources is stored, a so-called carbon dioxide sink is created, as biogenic carbon is removed from the cycle.

Carbon Capture and Storage (CCS): CO₂ is collected and stored in the subsurface or as carbonates in minerals, such as mine waste.

Carbon Capture and Usage (CCU): CO₂ is collected and used as a raw material for the production of fuels or chemical products like plastics.

1.3 How will future steel production with low emissions look?

Access to new technology and global and regional resource constraints are likely to govern the development of the steel landscape. The points below are intended as a basis for discussion.

New Technology: 1) The only chance for the blast furnace process to survive and evolve into a low greenhouse gas emission process is to convert it into an oxygen blast furnace with top gas recirculation and carbon capture and storage (CCS) for the generated carbon dioxide. 2) Another main alternative to the blast furnace, proposed for producing liquid pig iron, involves first reducing the ore in a direct reduction furnace using either hydrogen or bio-syngas and then melting it in an electric furnace. This electric furnace can be either an electric arc furnace, established and capable of producing steel from direct reduced iron (DRI) and scrap in various proportions, or a so-called electrothermic pig iron furnace where liquid pig iron with high carbon content is produced. The advantage of producing liquid pig iron before the steelmaking process is that impurities in the ore can be efficiently separated, reducing the burden on the subsequent steelmaking process, which is more sensitive to high impurity levels. Thus, melting in an electric arc furnace is suitable when low-grade ore is available, while melting in an electrothermic pig iron furnace (or in the blast furnace) is suitable for higher impurity levels. The electrothermic pig iron furnace cannot be considered new technology but has had limited use for DRI until now. For hydrogen production, the development of water electrolysis technology is crucial, along with the production of electric power for electrolyzers.

Resource Constraints: It is reasonable to assume that future choices of implemented technology will be shaped by the availability and price of, in addition to capital, ore, scrap, electricity, coking coal, natural gas, biomass, and carbon dioxide sequestration, all of which affect the ability to produce steel at a competitive cost.

Ore: The iron ore pellets used today for gas based DRI and hot briquetted iron (HBI) production, known as DR pellets, have a lower gangue content than those used for blast furnaces, known as BF pellets. To some extent, the amount of DR pellets can be increased by reducing the gangue levels in ores where possible. However, most of the reduction must be done in either an oxygen blast furnace with top gas recirculation and CCS or a direct reduction furnace + electric pig iron furnace.

Scrap: Steel production has doubled in recent decades, leading to an increase in the availability of scrap for recycling as short to medium-lived products are discarded. At the same time, India claims that it will significantly increase its steel production, likely impacting the global ratio between ore-based and scrap-based steel, although local markets will be affected differently. In a scenario where blast furnaces are shut down in Europe and replaced with electric arc furnaces without securing the

supply of direct reduced iron (DRI) or hot-briquetted iron (HBI), a shortage of clean iron raw material may arise. The main contamination in scrap currently is copper, which enters the recycling streams through components like entire electric motors and bearings in piece scrap flows, and copper wires that get entangled in magnetic iron in fragmented scrap and are not sorted out in magnetic separation. The European Union (EU) has a net export of scrap that could be utilized, provided it undergoes processing, primarily targeting copper removal.

Electricity: Access to and the price of electricity will likely be crucial for hydrogen production for iron ore reduction in the coming decades, given competitive alternatives.

Coking Coal: Increasing prices of coking coal indicate an impending shortage, supporting a trend where coking consumption is reduced, and the process is replaced with alternative methods, at least partially. The extent of the shortage will influence the pace of the transition.

Natural Gas: Natural gas is not scarce, but prices vary greatly from the Middle East and North Africa (MENA), where prices are very low, to Europe, where they are high. Transportation is possible but expensive. Natural gas is often found in areas where the subsurface is suitable for CCS.

Biomass: By-products from forestry and agriculture are well-suited for gasification, and the refinement value for reduction is higher than for traditional uses such as electricity and heat. Therefore, availability is good in areas with forestry and agriculture. The material is bulky, so facilities likely need to be limited in size to avoid high transportation costs.

Carbon Dioxide Sequestration: Local markets for CO₂ and opportunities for CCS will likely influence locations and technology choices.

1.4. Alloying elements and their impact on the carbon footprint of steel

Alloys hold a special position, not only because they represent an investment that has incurred significant emissions and should, therefore, be utilized efficiently, but also because they can be considered a critical resource, given that Europe has limited access to such materials.

1.4.1 The significance of alloying elements for the properties of steel

Steel, in its simplest form, is an alloy of iron and up to 2% carbon, which is an extraordinarily important alloying element due to its ability to impart various properties to steel through heat treatment. Other alloying elements can alter electrical properties, enhance corrosion resistance, increase deformation hardening, make the material more heat-resistant, improve weldability, and change toughness or hardness, among other effects.

The same metal can serve as a valuable alloy in one type of steel and act as an impurity in another. Copper, for instance, is generally considered an impurity in scrap metal, but it is the element responsible for giving Corten steel its excellent corrosion-resistant properties.

1.4.2 Emissions of greenhouse gases in the production of alloying elements

The ores used in the production of alloying elements generally have significantly lower metal content than iron ores. This necessitates breaking, crushing, and enriching larger quantities of material compared to iron production. Some ores are complex, requiring the separation of multiple components to obtain a material suitable for alloying. The increased mass handling and complexity result in a carbon footprint that can be two times (e.g., certain manganese) to twenty times (e.g., certain nickel) higher than that for iron.

1.4.3 Recycling of alloying elements in Steel

Four factors determine how well alloying elements in steel can be recycled to retain their value as alloys: identification, sorting, recycling method, and covering the costs of identification and sorting.

Identification: When a steel item is cast, it has a steel code that indicates its composition. The longer the steel code can be linked to the material, the better. In a steel mill and during manufacturing processes later in the chain, the steel code is known when internal scrap is generated, for example, during turning, punching, cutting, grinding, etc. In good practice, this information can accompany the material back to the one who will mix the scrap and create a new melt and a new cast item. Scrap where information about the steel code is not preserved, which is the norm for collected scrap, can be analyzed with a handheld X-ray analyzer. This is done regularly when there are larger quantities of similar materials. Complex products such as cars and appliances are fragmented. In this process, the scrap pieces are sorted into a magnetic and a non-magnetic flow. The pieces can then be further identified with laser technology (LIBS) or X-ray methods for additional separation into fractions, for example, using robot technology. Figure 2 shows two pieces of fragmented scrap from the magnetic flow. For magnetic scrap, the alloy value is not considered high enough today to justify automatic sorting alone. For non-magnetic scrap, stainless steel is sorted, in some facilities, into a fraction with molybdenum and one without.

Sorting: A steel mill can have hundreds of different steel codes in its production program but has significantly fewer storage spaces to keep the items separate. The ability to keep different materials apart in a cost-effective way is a key issue throughout the steel life cycle. An automatically sorted flow of fragmented ferritic scrap in different alloy classes poses a logistical challenge.

Recycling method: Steel production in both converters and electric arc furnaces currently occurs under oxidizing conditions. Oxygen is blown in to create a foaming slag, remove excess carbon, and eliminate impurities such as phosphorus. In this process, manganese, chromium, vanadium, and some of the iron are also oxidized into the slag. In some cases, it is possible to melt under reducing conditions to retain the alloys in the steel. This is done, for example, with steels with high manganese content. Foundries use induction furnaces without oxygen, so they can better utilize alloys in scrap but, in turn, depend on clean raw materials without impurities that need to be oxidized away. Finally, utilizing alloying elements in steel requires the ability to handle smaller scrap batches and optimize production to fully utilize the alloy content.

Covering the Cost of Sorting: Improved identification and sorting create both a large flow of scrap that is cleaner than the inflow of unsorted scrap and multiple smaller outgoing flows of alloyed scrap. Both represent a higher value than the unsorted scrap. If the overall value increase is higher than the costs of identification and sorting, the action becomes, at worst, cost neutral. To ensure this, continued and deepened dialogue between the supplier and the customer is necessary.

1.4.4 Handling of recycling of iron and alloys in laws, standards, and initiatives

Historically, alloys in low-alloyed scrap have been treated as contaminants. Trading systems have classification rules for high-alloyed scrap where the alloy price justifies more accurate sorting.

Scrap quality is addressed in EU Regulation 333/2011, which includes descriptions of scrap classes and requirements, including analysis, for a material to cease being waste according to the waste directive. Regarding ferritic scrap, there are limitations on the maximum allowable alloy content, as they are considered contaminants. Apart from ferritic stainless scrap with alloy contents above 10%,

there are no ferritic scrap classes with minimum alloy values, and thus, they are seen as valuable metals.

In life cycle assessments, whether following LCA standards or new initiatives, primary alloys are treated as Scope 3, i.e., processes upstream of steel production contributing to greenhouse gas emissions, and the higher carbon footprint affects the product. However, in most standards and initiatives, scrap and alloys in scrap have no impact other than the contribution to greenhouse gas emissions from transport and handling processes. In environmental declarations according to standards EN 15804 and prEN17662, the environmental value of recycling can be provided as additional information. The reduced value of not fully utilizing the alloy value should be evident in the declaration according to the standards.

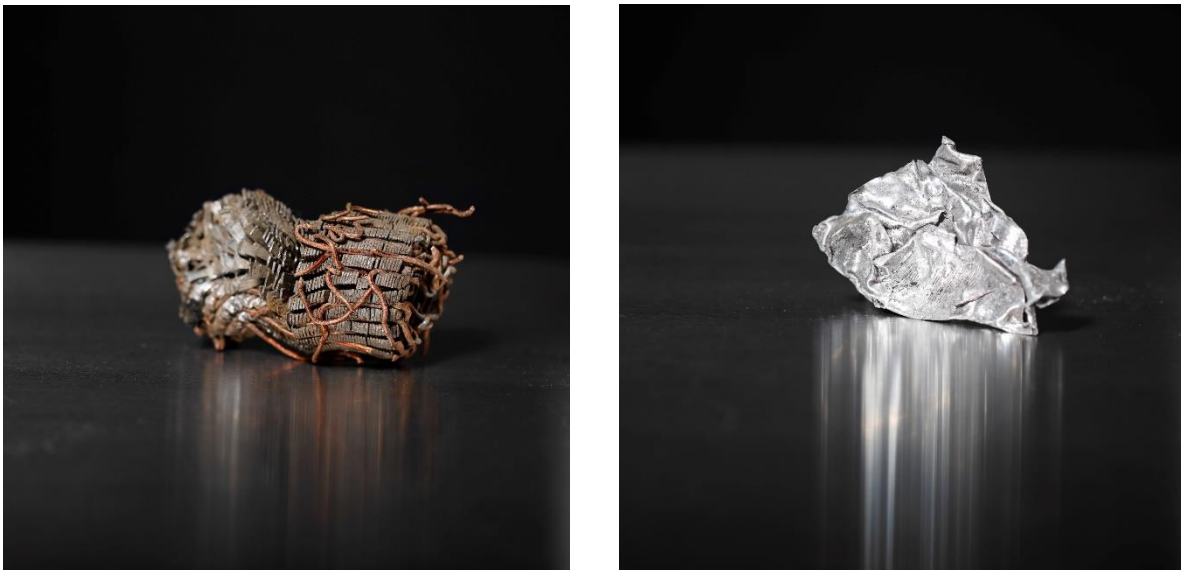


Figure 2. Two pieces of magnetic scrap from a fragmentation facility. The piece on the left contains copper wires that have not been separated. The piece on the right is clean but may be unalloyed from a lamp, high-manganese steel from a bumper, tin-plated steel from a canned food container, or stainless steel from a refrigerator. The scrapped products in the fragmentation facility have likely been optimized so that maximum limits for copper, tin, manganese, chromium, or nickel are not exceeded. However, the value of the alloys has been lost, and they have become impurities. Photo: Per-Erik Berglund, Znapshot.