3. Primary/secondary raw materials

Although in Switzerland chromite is found on the southern side of the Alps and nickel in many Alpine valleys[32], extraction is currently not worthwhile, due to economic reasons. As no high-quality stainless steel is produced in Switzerland, the recovery from secondary raw materials remains the largest source of stainless steel.

Fig. 4 shows the development of stocks in landfills[2,4,5,13] and use[14,28,29,40] in Switzerland. In 2010, the quantity of stainless steel in landfills was half that in vehicles (transport stock). By 2030, all in-use stocks are expected to be in a steady state.[28]

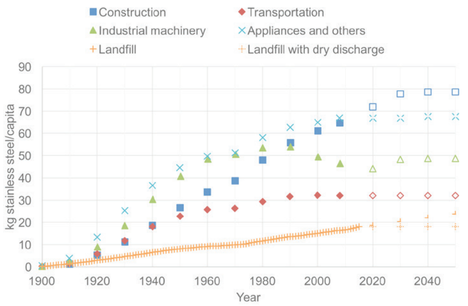

Fig. 4 Swiss stainless steel stocks. Forecasts as of 2008 (stainless steel in use) and 2015 (landfill) are shown as empty forms or dotted crosses. The extensive recovery of stainless steel from incinerated waste would lead to a significantly smaller repository (dotted cross) in 2050 than if no recovery took place (halved cross).

Further recovery of stainless steel takes place from the processing of dry discharged slag. With a 0.5% stainless steel fraction from raw slag, this would correspond to 3'000-4'000 t/year for all of Switzerland. This in turn leads to smaller landfill sites.

Fig. 5 shows the annual quantities of goods imported into Switzerland for the five use categories as well as waste quantities and their respective stainless steel contents. Not shown is the amount of waste from the building and infrastructure sector, which is estimated at 13 million tons, and its stainless steel content, which is approximately 0.04%.[30,pers. communication, K. Kohler, R-Suisse, 21.08.2017]

Due to the very high stainless steel content in metal goods, this use category represents the largest potential source of secondary stainless steel in Switzerland, followed by industrial machinery. At the same time, metal goods have the lowest collection and recycling rates within the five use categories.[30] Gas and steam turbines also have major potential for recovering stainless steel.

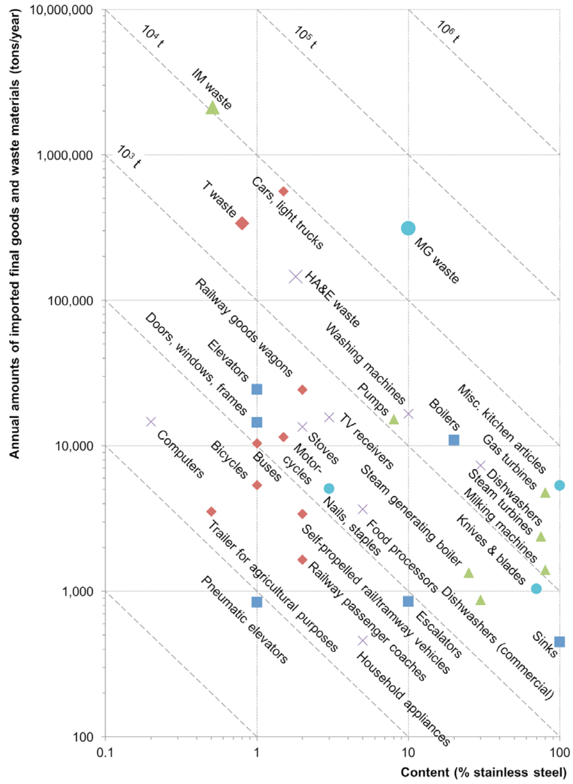

Fig. 5 Tonnage-ore grade diagram for imported goods and waste groups[7,9,10,17,23,30,34,pers. communication, K. Kohler, R-Suisse, 21.08.2017] (■: B&I, ◆: T, ▲: IM, ✖: HG&E, ●: MW). Example as a reading key: 560'000 tons of small vehicles with an average stainless steel content of 1.5% are imported into Switzerland, which corresponds to 8'400 tons per year of pure stainless steel. The B&I waste group, with 12.6 megatons/year and 0.043% stainless steel content, is outside the graphic area.

4. Environment

Chromium is an essential micronutrient for humans. Hexavalent chromium, on the other hand, is highly mutagenic and is associated with an increased incidence of bronchial cancer in chronic occupational exposure.[27] Nickel is considered a trigger for contact allergies, nickel compounds are also carcinogenic.[37]

The production of ferronickel is an energy-intensive process. **Fig. 6** shows the cumulative energy demand of Greek ferronickel production from primary raw materials up to refining. Greece is one of the seven largest ferronickel producers in the world. Smelting requires the most energy, followed by refining. This energy demand can hardly be reduced by switching to renewable energies or recycling waste (e.g., slag) as building material. The energy credits acquired in this way do not play a role in the ranking. The potential for improvement is therefore very small.

A comparative life cycle assessment for three stainless steel classes shows that secondary production from stainless steel scrap performs better than primary production (**Fig. 7**)[8]. These values refer to the global stainless steel industry. Calculations by the Frauenhofer Institute have shown that secondary production saves 4.5 tons of CO_2 per tonne of stainless steel scrap used.[24] The main savings are made thanks to recycled nickel (72.5%), followed by chromium (21.1%). This reveals the enormous ecological optimization potential that lies in the expansion of stainless steel scrap recycling.

Already today, 500 kg of stainless steel scrap is used per ton of stainless steel. An increase to 75% is already being targeted for.

In short, it can be said that the expansion of stainless steel scrap recycling offers great potential for ecological optimisation. Up to now, the cumulative energy demand and greenhouse gas emissions have been the main focus of research. No information on other environmental indicators such as biodiversity losses or ecotoxicity is currently available.

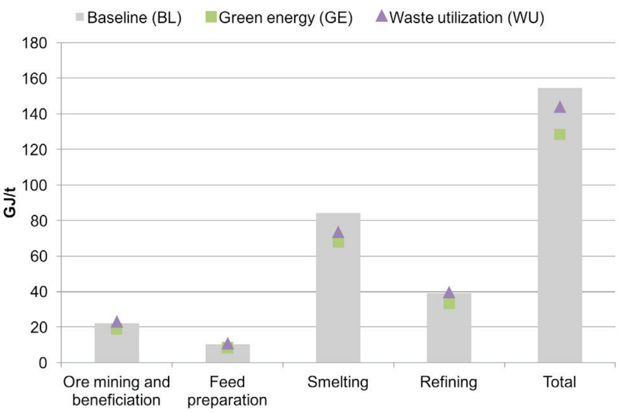

Fig. 6 Cumulative energy demand of ferronickel production in Greece.[3] In addition to the current situation, two scenarios were examined: switch to green energies (GE, ■) and waste utilization (WU, ▲).

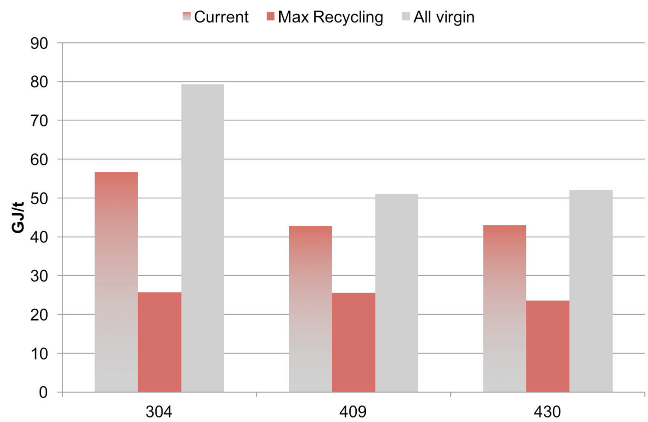

Fig. 7 Cumulative energy demand of the production of three austenitic stainless steels of varying qualities (AISI 304, 409 und 430).[8]

5. Technology

In primary production, stainless steel can be produced in various ways (**Fig. 8**). Ferrochromium is produced exclusively in electric arc furnaces with the addition of fluxes and reducing agents.[27] Nickel is nowadays mined from sulfidic (60%) and lateritic (40%) ores. In lateritic ores, the nickel concentrate is processed either pyrometallurgically to ferronickel or hydrometallurgically to nickel oxide. In the case of sulfide ores, the nickel concentrate is processed exclusively via the pyrometallurgical route.[16]

Today in secondary production there are several pathways from waste or scrap to stainless steel. Nickel-rich scrap is utilized directly in electric arc furnaces. Nickel-rich production waste from special steel companies (e.g., fly ash, chips, scale) is processed into a stainless steel melting material (**Fig. 8**).[16]

Stainless steel scrap is collected, processed, and remelted.[27] In Switzerland, the stainless steel cycle is closed through segregated collection. The physical form of the steel scrap can then be changed by processing in shredder plants or by shearing.[27] Certain materials require cleaning or sorting prior to recycling, as they may contain residuals from shredder plants such as aluminum or copper.[15] For this purpose, established processes such as magnetic and eddy current separation are used in Switzerland. Three further technologies make it possible to sort stainless steels with different chemical compositions: (i) mobile/portable optical emission spectrometers, (ii) colour sorting, and (iii) laser emission spectrometry.[15,41] These technologies are, however, not yet being used in Switzerland. However, the fourth industrial revolution (Industry 4.0), i.e. digitization and networking along value chains[37], could offer new opportunities for such technologies.

An alternative to energy-intensive remelting is "remanufacturing", that involves the use of entire old parts containing stainless steel in new vehicles, buildings, or machines.[12,22]

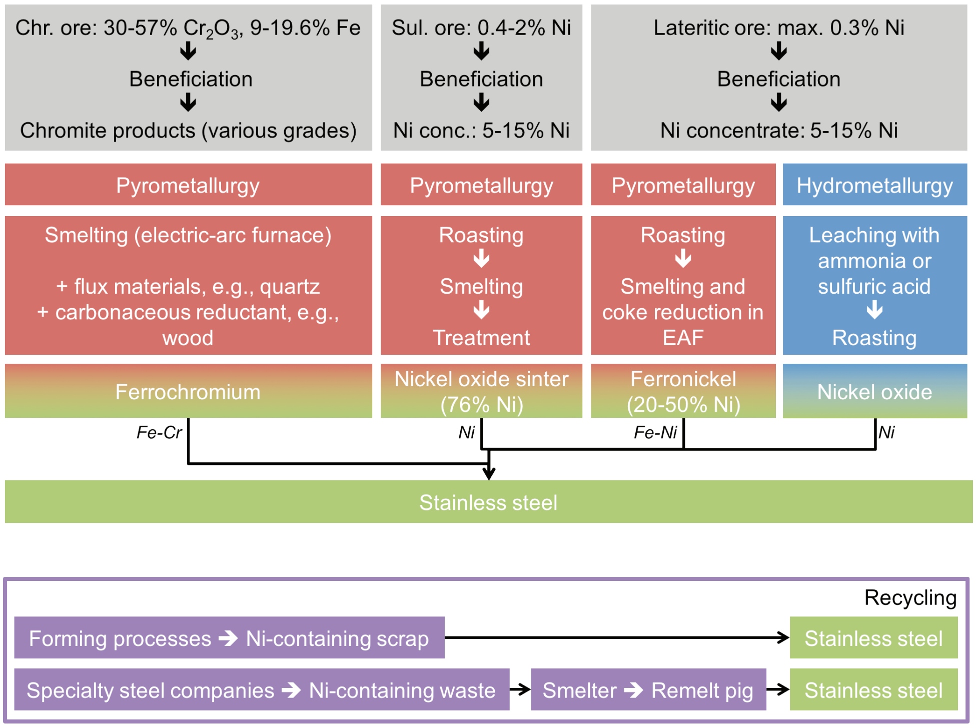

Fig. 8 Primary and secondary production of stainless steel[16, 27, 37] (Chr: chromite, conc.: concentrate, sul.: sulfidic). Not shown are the iron production from iron ore[19], as well as the remelting of stainless steel scrap and remanufacturing as recycling paths.

6. Economy

In 2015, 180'000 tons of stainless steel products (i.e., products with stainless steel as the main component) worth CHF 880 million were imported into Switzerland. By contrast, 120'000 tons worth CHF 600 million were exported (**Fig. 9**).[9] Both the import and the export of one ton of stainless steel cost an average of CHF 5'000 in 2015. Exports consisted in cheap scrap and more expensive goods. In terms of volume, hot- and cold-rolled stainless steel accounted for the bulk of imports, while exports consisted mainly of scrap. In terms of value, goods accounted for the majority of imports and exports. Metal slab and semi-finished products are insignificant in terms of quantity and value.

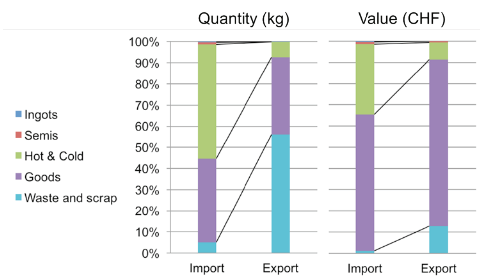

Fig. 9 Imports and exports of metal slab (dark blue), semi-finished products (red), hot- and cold-rolled stainless steel (green), goods (violet), and waste and scrap (light blue) with stainless steel as the main component in 2015.[10]

Fig. 10 shows the import prices of stainless steel, ferrochromium and selected alloying elements as well as the export price of stainless steel scrap between 2005 and 2016. Stainless steel and nickel have become around 50% cheaper in this period, while ferrochromium has become twice as expensive. The hike between 2006 and 2008 due to increased energy prices is visible. Stainless steel prices fluctuate less than raw material prices. Molybdenum and titanium prices are particularly volatile. In the case of nickel and chromium, there is a risk of export restrictions being imposed by mining countries, as mining takes place primarily in Indonesia and the Philippines, or in South Africa and Zimbabwe. In addition to geopolitical factors and energy prices, monetary policy also plays a role. The stainless steel scrap export price trend is similar to that of imported nickel and is therefore subject to high volatility.

The stainless steel market price in 2014 was nine times higher than that of carbon steel.[20] This price difference is an incentive to sort between the two types of steel. The collection costs consist of several components. Transport currently costs around CHF 180 per hour. Larger objects must be shredded with scissors, which costs between CHF 50 and CHF 60 per tonne.[pers. communication, K. Kohler, R-Suisse, 21.08.2017]

Possible barriers to an increase in the separate collection of stainless steel scrap are still too small price differences between carbon and stainless steel scrap, the high volatility of the stainless steel scrap price, and a lack of competition due to the disposal monopoly. In addition, there are technical barriers such as miniaturization and shorter lifetimes for certain products. However, the main driver is the extraction of primary resources. Today, nickel is expected to have a static range of 35 years.[39]

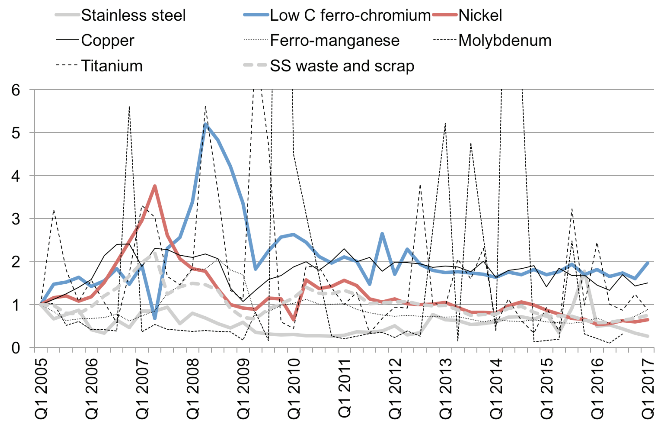

Fig. 10 Indexed Swiss quarterly import prices of stainless steel (SS) and selected alloying elements and export prices of stainless steel scrap from May 2005 to October 2016[9] (1: price in first quarter 2005).

7. Society

Stainless steel is not produced in Switzerland. Stainless steel scrap is collected separately, partially sorted, and physically processed before being exported for remelting. These activities generate little added value.

The increased networking of recycling actors (i.e., Industry 4.0) and the increased use of old parts (i.e., remanufacturing) could result in more scrap remaining in the stainless steel cycle and thus promote the conservation of primary resources. The implementation of both concepts would also have social consequences.

Industry 4.0 is intended, among other things, to increase industrial productivity and enable new business models.[36] Industry 4.0 concepts are supported by the "Industry 2025" platform - an initiative of the associations swissT.net, electrosuisse, asut (Swiss Telecommunications Association) and Swissmem (www.industrie2025.ch). The aim of the "Industry 2025" initiative is to secure and expand the competitiveness of Swiss companies and Switzerland as a business location. Particularly important for the segregated collection of stainless steel scrap is the working group "Introduction to Industry 4.0", which is developing a toolbox for the implementation of digital business development in SMEs. In addition to increased sorting, Industry 4.0 also offers new perspectives in resource efficiency.[33]

Fig. 11 Evaluation of remanufacturing and manufacturing by means of lean manufacturing indicators[18] (4: leanest scenario, 1: least lean scenario, DfRem: "Design for Remanufacturing").

Remanufacturing is a promising strategy to increase productivity and reduce environmental impacts.[11] The topic of remanufacturing is not yet treated as intensively as Industry 4.0 in Switzerland. One possible reason for this is the limited application of the principles of lean production to remanufacturing in comparison to conventional manufacturing.[18] However, similar to Industry 4.0, remanufacturing provides new opportunities to the Swiss machinery, electrical and metal (MEM) industry[35]: the development of new technologies in the field of remanufacturing, the recycling of old parts, and a secure supply of raw materials. Industry 4.0 could overcome some of the most important challenges of remanufacturing[6], namely the lack of information and cooperation, inefficient production planning and control, and the low level of automation (**Fig. 11**). An evaluation criterion is the "Design for Remanufacturing" (DfRem), i.e., the design of products which are suitable for remanufacturing. Since no DfRem is used in conventional manufacturing, remanufacturing also gets a poor score in this respect.

Both Industry 4.0 and remanufacturing provide new horizons, not only in terms of closing stainless steel cycles, but also in terms of securing and creating jobs in Switzerland.

8. Resource management: the overall situation at a glance

An evaluation of the urban mining potential of stainless steel based on qualitative expert assessment shows that there is still a need for action in this area (**Fig. 12**).

The Swiss Association for Steel and Metal Recycling (VSMR) represents companies that collect, sort, process and/or export stainless steel scrap. In order to improve the collection rate of stainless steel, the VSMR is increasingly focusing on vocational and continuous training for the efficient handling of stainless steel scrap. The new waste regulation has also led to closer cooperation between the VSMR, the Swiss Excavation, Dismantling, and Recycling Association (ARV), and Biomasse Suisse, which should support increased optimal solutions for the recovery of stainless steel scrap.

Additionally, the Swiss Professional Association for Training in Recycling (R-Suisse) is currently strengthening the vocational and continuous training of recyclers. In the long-term, more skilled workers and increased skills could contribute to the closure of the stainless steel cycles.

Technological developments should be promoted and monitored, for example through the support of pilot projects.

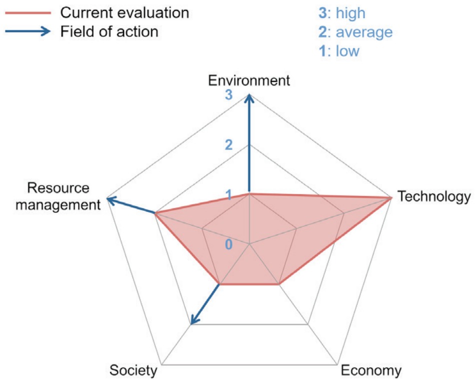

Fig. 12 Evaluation of the urban mining potential of stainless steel (all end uses) based on qualitative expert assessments. **Criterias:** *Environment:* More environmentally friendly secondary production, but until now only the cumulative energy demand has been considered. *Technology:* Sorting technologies available in Switzerland and interesting opportunities due to digitization. *Economy:* Small price difference as a barrier to sorting, high volatility. *Society:* Implementation of digitization and remanufacturing to increase added value. *Resource management:* Optimisation of high-grade recycling, e.g., by defining the state of the art.

Open questions

1. What are the environmental impacts of primary and secondary production besides cumulative energy demand?
2. How can the downcycling of metal goods be avoided and how much would it cost?
3. How can a nationwide recovery of stainless steel from wet or dry discharged slag be optimized?
4. How can the incentives for separate collection of stainless steel be increased and what costs would this entail?

Literature
Due to limited space, the bibliographic references are summarised in a separate document:
http://www.tdlab.usys.ethz.ch/awel_stahl_lit_en.pdf

This substance dossier was created by Grégoire Meylan from the USYS TdLab at ETH Zürich for the AWEL.
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Amt für Abfall, Wasser, Energie und Luft
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Stainless steel

1. The importance of stainless steel

Stainless steel is the industry-specific and colloquial term for rust-resistant steels, and takes over important functions in a modern society. It is used in metal products or mechanical engineering (**Fig. 1**) and in 2013 accounted for 2.4% of global steel production.[14,40] Worldwide, over 32'000'000 tons of stainless steel were produced in 2015, an increase of 33% compared to 2009.[24]

Stainless steel encompasses a group of iron-carbon-chromium alloys which are characterised by their resistance to rust, acids, and heat. The most important raw materials for stainless steel production are iron and ferrochromium, produced from chromite ore.[27] Nickel is used in non-magnetic (austenitic) stainless steels to increase resistance to low and high temperatures.[1] Ferronickel from lateritic ore is an important raw material in this process. Numerous other elements such as Mn, Mo, Cu, Ti, Se, Nb, Si, Co, Ca, N, P, S[1] are added to stainless steel as alloys in order to optimize characteristics such as heat resistance, strength, malleability, and resistance to corrosion and oxidation. China represents 52% of global stainless steel production, followed by other Asian countries.[14] Chromite is mainly mined in Africa – in 2014 Africa covered 55% of the global chromite market.[14] By contrast, the two largest nickel ore producers in 2014 were the Philippines and Indonesia with 17% and 9% of global production respectively.[14] **Fig. 2** shows the development of metal contents in ore as well as their price development. Nickel concentrations are steadily decreasing in various mining regions. Prices for nickel, ferrochromium, and stainless steel scrap follow a similar trend, albeit at very different price levels. Energy prices and geopolitical events play an important role in this trend.[26]

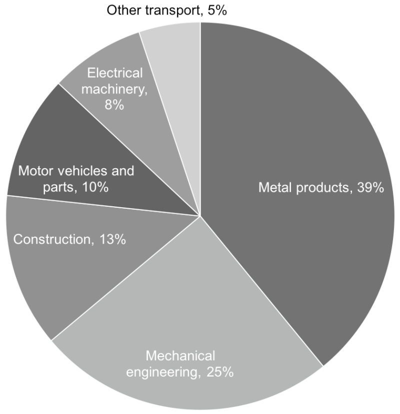

Fig. 1 Stainless steel usage[14] (in percent). In 2013, 39'000'000 tons of stainless steel were produced worldwide.

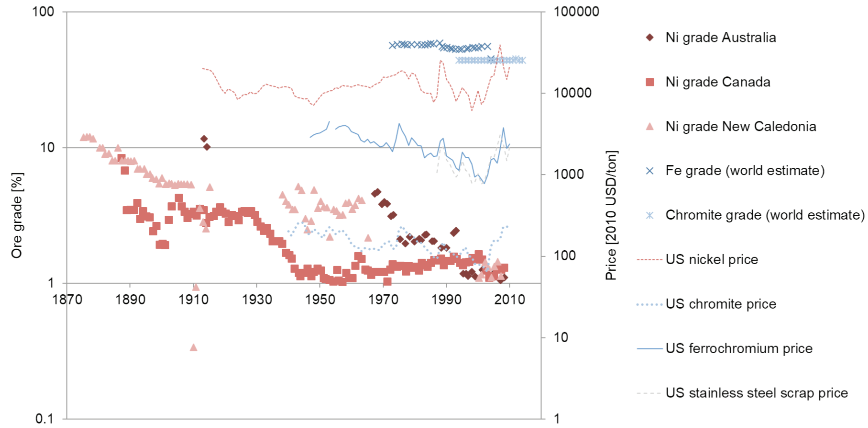

Fig. 2 Ore grades[21,25] (left axis) and inflation-adjusted ore and metal prices[38] (right axis).

2. Understanding the system

The largest source of stainless steel comes from abroad, through imports of flat and long semi-finished products and imports of stainless steel products (**Fig. 3**), since no high-alloy stainless steel is currently being produced in the two existing Swiss steel mills. The largest sink corresponds to the amount that is used annually (2005: 51'000 tons), followed by the export of stainless steel scrap. Per capita consumption in 2005 was around 14.1 kg of stainless steel, slightly more than the average for industrialized countries (11.9 kg).[31] Metal goods such as knives, nails, staples, and kitchen utensils represent both the most important applications and also the largest source of waste. On the other hand, the reduction of the stainless steel stock in the use category of industrial machinery is remarkable. This stocks depletion takes place due to the continuous liquidation of such machines.

In 2005, the collection and recycling rates were 71% and 62%, respectively. The difference corresponds to the stainless steel scrap that is fed into the carbon steel cycle. In this process, nickel, chromium, and their respective properties are lost.

The scrap recyclers collect metal waste from trade and households, old appliances, and to some extent end-of-life vehicles, separate it, and sell the stainless steel scrap to regional traders, smelters in nearby countries, or trading companies, which in turn export large quantities to China and Turkey.[pers. communication, K. Kohler, R-Suisse, 21.08.2017]

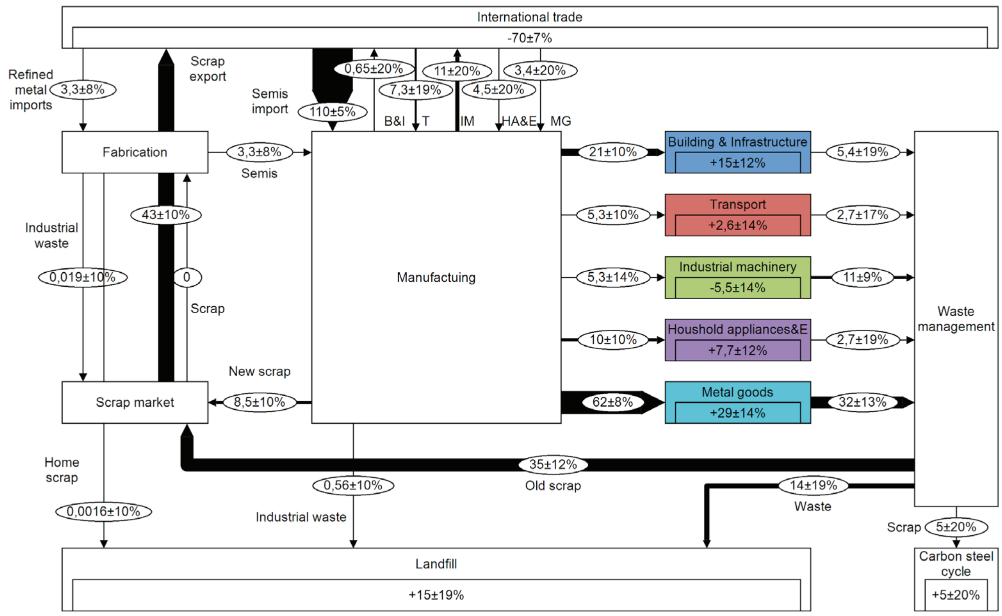

Fig. 3 Stainless steel flows 2005 (1'000 tons/year[30,pers. communication, K. Kohler, R-Suisse, 21.08.2017], B&I: building and infrastructure, T: transport, IM: industrial machinery, HA&E: household appliances and electronics, MG: metal goods).

Thanks to optimized metal recovery from incineration residues, stainless steel is recovered from residual waste by means of downstream infrared sorting. Today, stainless steel is recovered with this technology in large quantities and high quality from dry discharged slag at the municipal solid waste incineration plant (MSWI) in Hinwil, located in the canton of Zurich. Throughout Switzerland around 1'500 tons/year of stainless steel of different qualities are recovered from incineration residues today. As seen in the example of the Hinwil MSWI plant, the latest technology makes it possible to increase the recovery rate of high-quality stainless steel by a factor of three. This would reduce the material flow of stainless steel from MSWI to landfill by 25%.