3. Primary/secondary raw materials

Most geogenic zinc deposits of Switzerland are situated in the eastern and western Swiss Alps and in Tessin.[36] At present, extraction is not profitable. In contrast, Switzerland can today rely on large secondary zinc reserves: approx. 1'000'000 tons of zinc are stocked in Swiss landfills, which is the equivalent of around 120 kg per capita in 2015 or 130% of the zinc in-use stock (**Fig. 4**). The in-use stock is the amount in active use.

Today's economically recoverable geological deposits exhibit a maximal ore grade of 70 g Zn/kg. Waste electric and electronic equipment and end-of-life vehicles contain some 5–10 g Zn/kg (**Fig. 5**). Construction and demolition waste contains 0.9 g Zn/kg, while fly ash from MSWIs have some 40 g Zn/kg. The highest zinc concentrations are found in filter dust from steel works with 150–450 g Zn/kg and zinc oxides from Waelz kilns with 550–700 g Zn/kg. The in-use zinc is contained mainly in construction, vehicles, and smaller products ending up in MSWIs. 34% of the waste zinc collected in Switzerland in 2010 was rerouted to the zinc cycle.

The evolution of the in-use zinc stock per capita shows a decline as of 2000 and a flattening as of 2010 (**Fig. 4**). The amounts landfilled in 2050 depend on the deployment of acid washing of fly ash and the subsequent metal recovery. Should all fly ash be treated with these two technologies, the landfill stock would amount to 144 kg of zinc per capita by 2050. The landfill stock would rise to 153 kg/capita if neither technology were taken up and the decision was made to landfill fly ash. The full deployment of fly ash treatment could thus reduce the future landfill stock by a quarter in comparison to the total absence of these technologies.

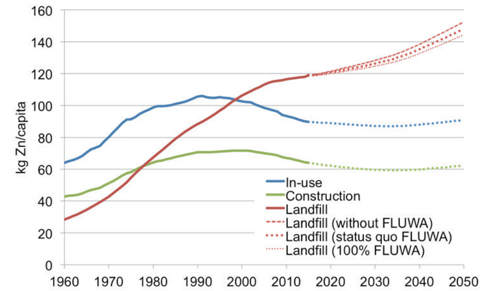
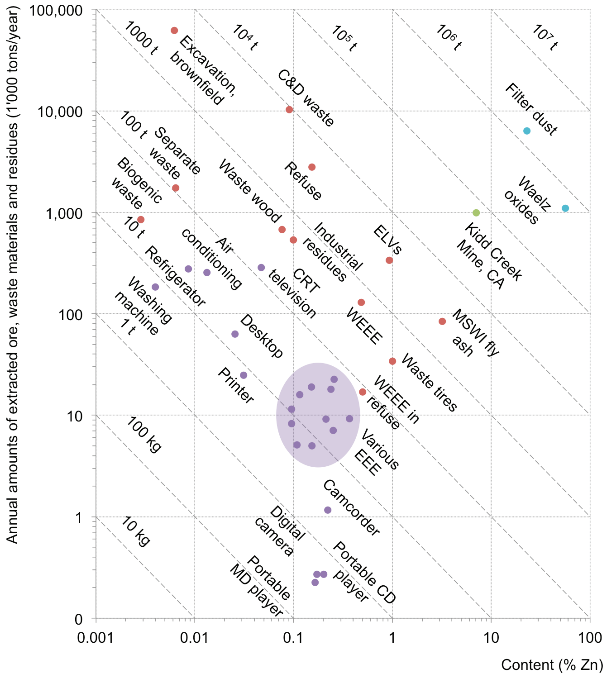


Fig. 4 Evolution of zinc stocks in Switzerland (based on Hügi et al.[19], Kral et al.[23], Meylan and Reck[24], Schlumberger[31]). The figure highlights the landfill stock evolution, if the deployment of acid washing of fly ash and subsequent metal recovery remains constant after 2015. Assumptions: constant zinc demand as of 2015, population growth as in the Federal Statistics Office's "average scenario" (A-00-2010)[2], constant recycling rates for all other waste streams.



▶ **Fig. 5** Tonnage-ore grade diagram for primary production in the mine with the world's richest ore bodies (Kidd Creek, Canada) (green[13,16]) and secondary zinc resources (red: waste materials in Switzerland incl. fly ash from MSWIs[7,23,24,32], purple: waste electric and electronic equipment worldwide[29], light blue: filter dust from steelworks and Waelz oxides worldwide[1,24]). Example: 1'000'000 tons of zinc ore are mined each year in the Kidd Creek mine with an ore grade of 7%, which is the equivalent of 70'000 tons/a of pure zinc.

4. Environment

Zinc is an essential element for all life forms, plants and animals can either lack zinc or feel the toxic effects at high levels of exposure. Some plants lack zinc at concentrations in tissues below 20 ppm.[16] It is toxic above 400 ppm.[16] The use of zinc in coating and as mineral fertilizer and waste management are responsible for its emission into the soil and water bodies.[5] Some 126 g of zinc per capita were lost to the environment in 2013 in the Canton of Zurich.[23] Waste management is responsible for 52% of these emissions. 28% come from buildings and infrastructure, 11% come from agriculture, 9% come from waste water treatment.[23]

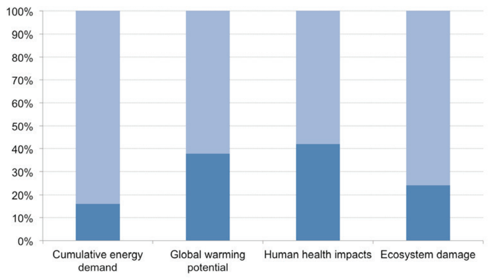


Fig. 6 Relative environmental impacts of life cycle stages of primary production[28]. The impacts on human health (DALY/kg) and ecosystem quality (Species.a/kg) are assessed with the impact assessment method ReCiPe Endpoint (H, World) v1.08[14] The impacts correspond to potential damages prior to normalization and weighting.

Zinc mines and mills release substances more toxic than zinc, for instance lead, copper, and cadmium.[16] The smelting and refining of zinc are most problematic when it comes to occupational heath. Standards for occupational exposure were therefore established to prevent metal fume fever.[16]

A life cycle assessment of all life cycle stages from mining to refining showed that purification and refining have the highest environmental impacts[28] (**Fig. 6**). This holds for zinc-lead mines, which make up some 93% of primary production.[28] Zinc (with a global production of 11'700 kt in 2008[40]) is ranked among the 10 metals with the highest CO_2 footprint (40 Mt CO_2 equivalents/yr) and highest impacts on human health and ecosystems. The cumulative energy demand of global zinc production amounted to 619 PJ in 2008, which corresponds to 1.3% of total metal production and the fifth rank among all metals.[28] This makes zinc one of the ecologically most relevant metals.

A comparative life cycle assessment shows (**Fig. 7**) how the SwissZinc process outperforms Waelz kilns as alternative to treat hydroxide sludge.[32] The investigated environmental indicators are the CO_2 footprint and the total Environmental Impact Points (UBPs). The SwissZinc process produces zinc metal. Waelz kilns recover zinc oxides as Waelz oxides, which substitute zinc ore. The better environmental performance of the SwissZinc process stems on the one hand from its higher product quality, as smelting of Waelz oxides is necessary. On the other hand, the SwissZinc process has a lower CO_2 footprint, as it does not require coke as reducing agent and the SwissZinc site at the MSWI in Zuchwil does not rely on fossil fuels.

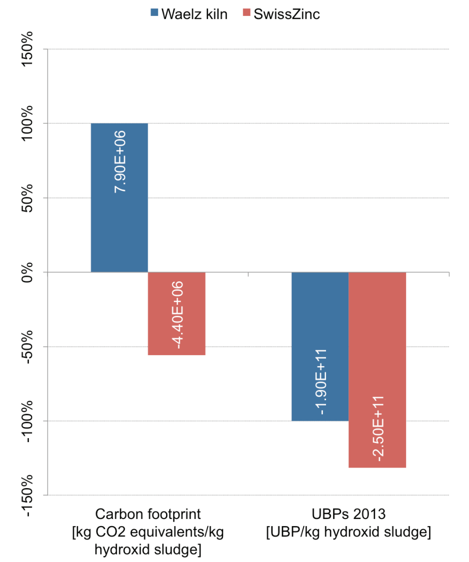


Fig. 7 Life cycle assessment of hydroxide sludge disposal in Waelz kilns (blue) and with the SwissZinc process (red). The relative values (%) refer to the Waelz kiln impacts. The UBPs 2013 and the CO_2 Footprint are calculated with the Method of Ecological Scarcity[11] and the CO_2 Footprint method[38], respectively.

5. Technology

Zinc is recovered from primary and secondary materials (**Fig. 8**). In the Kidd Creek mine, (s. Chapter 3, **Fig. 4**) zinc ore is extracted underground and in open pits.[16] The ore is first concentrated at the mining site and fed to subsequent smelting as concentrate. Smelting is performed in pyrometallurgical and hydrometallurgical processes. Today, hydrometallurgical processes account for 95% of global zinc production[33]; zinc concentrates are roasted and converted to zinc oxides, which then undergo sulphuric acid leaching, purification, and zinc electrolysis. The product is special high-grade zinc (purity >99.995%).

Because its environmental footprint is significantly smaller than that of primary production, zinc recycling is becoming ever more important in the framework of a sustainable circular economy. For instance, zinc-bearing filter dust from steel production is further processed for zinc recovery mainly in Europe, Japan, and the USA.[24]

The second recovery pathway, so far applied only in Switzerland, starts at MSWIs, where zinc accumulates in fly ash at an average of 40 g Zn/kg.[32] In the downstream FLUWA process, acid waste water, a by-product of flue gas treatment, enables the dissolution of heavy metals contained in fly ash – above all zinc.[3,31] The subsequent precipitation of dissolved metals yields hydroxide sludge. Foreign Waelz processes treat the resulting hydroxide sludge together with filter dust from steel works. Waelz oxides can be processed by smelters, in which they replace zinc concentrates proportionally.

The introduction of the FLUREC process in Switzerland demonstrated the feasibility of recovering zinc metal from MSWI fly ash (purity >99.995%). The technology builds on the FLUWA process, as it consists of purifying the FLUWA filtrate, increasing its zinc content by means of solvent extraction, and precipitating zinc metal through electrolysis. Extending the FLUREC process to all FLUWA-MSWIs is foreseen in the framework of the SwissZinc project. Such industry solution enables the fulfillment of the legal requirement on metal recovery.[35]

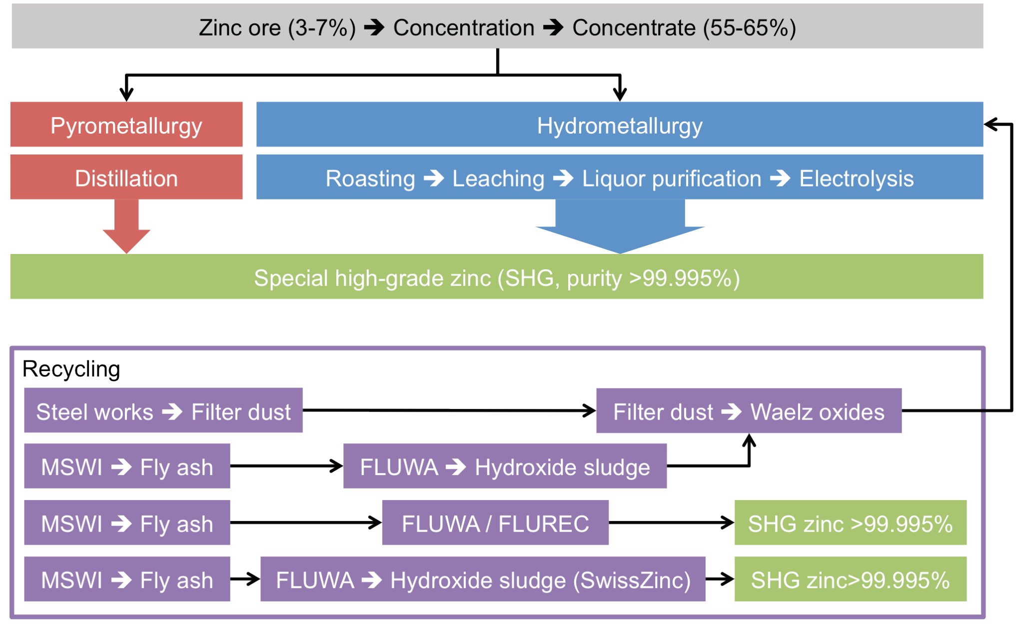


Fig. 8 Primary and secondary zinc production.[1,16,44,45] Different pathways exist in both primary and secondary production to yield zinc metal. In pyrometallurgy and hydrometallurgy, zinc passes from the oxidized form to the reduced one. The stages required to treat waste and residues from industry and waste treatment are highlighted in purple. For instance, waste incineration allows accumulating zinc in fly ash. Not shown on the figure are the production of other zinc products (e.g., zinc chemicals) and the possibility of remelting scrap from zinc alloys and brass.

6. Economy

2015 saw Switzerland import 21'000 tons of zinc products (i.e., products with zinc as main component) worth 63 million CHF; 16'000 tons worth 24 million CHF were exported[10] (**Fig. 9**). Raw materials make up the largest share of imports, while exports consist predominantly of goods. Unwrought zinc (i.e., zinc metal and zinc alloys) and semi-finished products represent together more than 90% of imports. 12'000 tons alone were imported as zinc metal showing a purity of more than 99.99% and worth 25 million CHF. This import category corresponds to the product substituted by the FLUWA and SwissZinc processes. Semi-finished products made up much of the exports, while scrap made up 15% of exports. The different nature of imports and exports affected the zinc price: while the import of a ton of zinc cost an average of 3'000 CHF in 2015, the exported ton was worth an average of 1'500 CHF. The zinc prices rose by some 40% between 2005 and 2016 (**Fig. 2**, **Fig. 10**). After the peak in 2006 and the economic crisis of 2008, the prices rose quickly again – presumably mainly thanks to speculative investments made because of the improving economic climate.[40] After that, the important price factors were the Chinese demand and the closure of large mines.[6,37] The danger arising from the emergence of oligopolies on markets is relatively small because the supply of zinc is possible in many countries on different continents.[24] The zinc import prices in Switzerland range from 1'900 to 2'800 CHF/t.[10] The USD-CHF exchange rate plays a role here as well. The price of landfilling MSWI fly ash in foreign underground deposits tended to decrease in the last years and amounted to 250 CHF/t. FLUWA can be considered as cost-neutral. The reduced landfill costs of output streams compensate the expenses entailed in FLUWA. Treating fly ash with the SwissZinc process will allow saving costs of underground landfilling, while securing the entire value chain in Switzerland. Switzerland can generate some 30 million CHF with this industrial solution. The net costs of zinc recovery from hydroxide sludge certainly depend to a large extent on the plant size and the actual zinc prices.

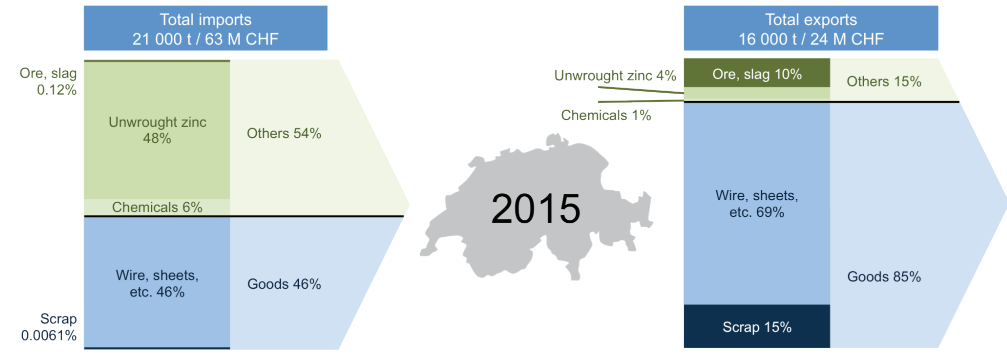


Fig. 9 2015 imports and exports of raw materials (green) and goods (blue) with zinc as main component[10] (Schl.: Schlacke). Filterstaub aus Strahlschrott, FLUWA-Hydroxidschlamm, KVA-Flugasche und verzinkter Stahl sind nicht enthalten.

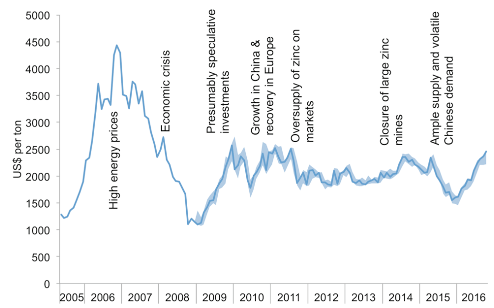


Fig. 10 Monthly zinc prices from May 2005 to October 2016.[6,12,37,40] The shaded area represents the difference between highest and lowest prices, while the dark blue line is the price at month's end.

Zinc **Zn**

1. The importance of zinc

Zinc is a key base metal of the industrial society and is also an essential element for all life forms.[17,22,40] Zinc coating prevents the corrosion of steel, and because of its low melting point it is also used in die casting of complex parts.[18] Zinc is mainly used in construction and transportation industries; in construction as galvanized steel, zinc alloys, and brass, and in transportation as galvanized steel, zinc alloys, brass, and zinc oxides for tire vulcanization (**Fig. 1**).

In nature, zinc occurs mainly as sulfide (sphalerite or zinc blende or wurtzite and hemimorphite or calamine), but is also extracted as oxide, carbonate, silicate, and compounds of the later.[16,18] Zinc compounds are generally colorless, except when zinc occurs with chromate.[15] Spharelite is deposited from hydrothermal solutions or simic or sialic magmas.[18] The largest zinc reserves are found in Australia, followed by China, Peru, Mexico, and the USA.[41]

The demand in zinc has grown over the last two decades, mainly driven by China's development. Yet despite this, the economically recoverable ore grades barely changed in Australia and Canada during this time (**Fig. 2**). In line with this, zinc prices did not rise significantly. That said, zinc prices soared twice in the past; during the oil price shock of 1973 and right before the global economic crisis of 2008.

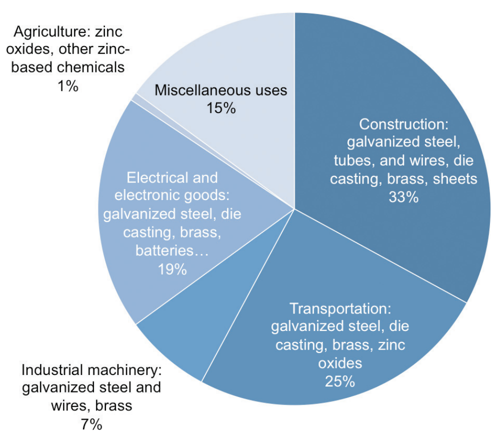


Fig. 1 Uses of zinc[24] (in percentages). In 2010, 13'000'000 tons of zinc were produced worldwide.

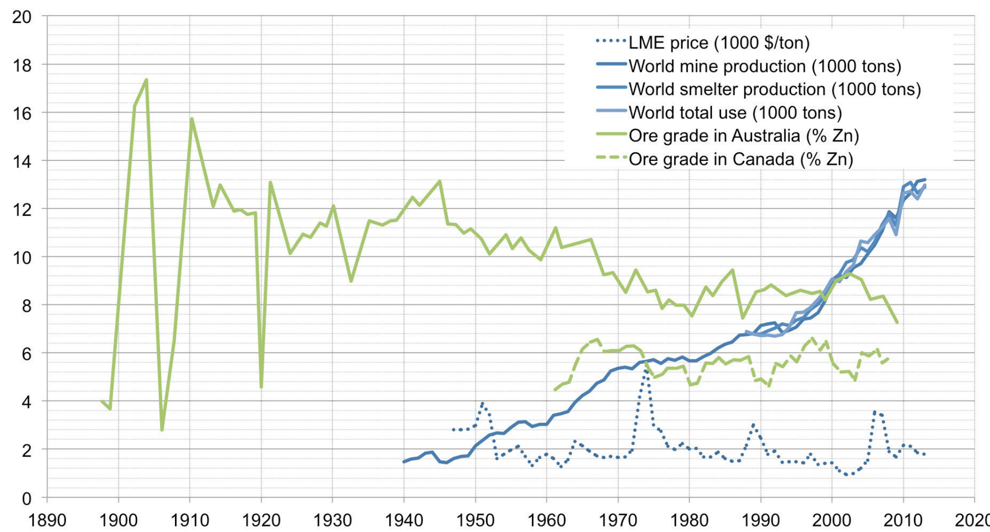


Fig. 2 LME (London Metal Exchange) price (1947-2013), inflation-adjusted (Source: Metals Week and Metal Statistics), mine production[20,42], smelter production[20] (1986–2013) and use (1988–2013)[20] of zinc, as well as zinc ore grade in Australia and Canada.[27]

2. Understanding the system

The zinc demand in Switzerland is entirely covered by imports and recycling (**Fig. 3**). Zinc is imported to Switzerland as zinc slab, semi-finished products and goods. The in-use zinc stock amounted to some 93 kg/capita in 2010 (global average of 24 kg/capita[24]). 5.3 kg/capita were imported in 2010. Every Swiss person needed ca. 4.5 kg of zinc back then, more than twice as much as the global average (1.9 kg). Meanwhile, every Swiss person generated 3.7 kg of zinc waste, of which 1.5 kg returned to production processes and 2.2 kg were landfilled in Switzerland or abroad. 0.23 kg were downcycled in cement plants among others. 1.3 kg were rerouted to the zinc cycle. Both the Swiss steel works and the municipal solid waste incinerators (MSWIs) play an important role in recycling. Steel works presently recover 1 kg Zn/capita as zinc-bearing filter dust.[39] In 2010, a third of fly ashes (2016: ca. 60%) from MSWIs was further processed for zinc recovery, corresponding to the recycling of 0.09 kg Zn/capita. Zinc recovery in MSWIs is made possible by acid washing of fly ash (FLUWA).[3,26,31] FLUWA produces zinc-bearing hydroxide sludge processed to zinc metal by means of foreign Waelz kilns just as filter dust from steel scrap. The rising costs of processing hydroxide sludge abroad make domestic recovery ever more attractive. Efforts focus on bringing about a central solution to the more complex part of metal recovery from fly ash in order to keep the costs of such recovery as low as possible. The plant planned for this purpose could process from 2021 on all Swiss hydroxide sludge to zinc metal by means of the SwissZinc process (see Chapter 4).[44,45] MSWIs could then recycle up to 0.26 kg Zn/capita from their fly ash.

50% of zinc entering MSWIs ends up in bottom ash as metal and mineral components.[25] MSWIs already partially recover brass (i.e., copper-zinc alloys), steel and zinc alloys. Low zinc concentrations among other factors hamper the recovery of zinc from non-metal fractions.

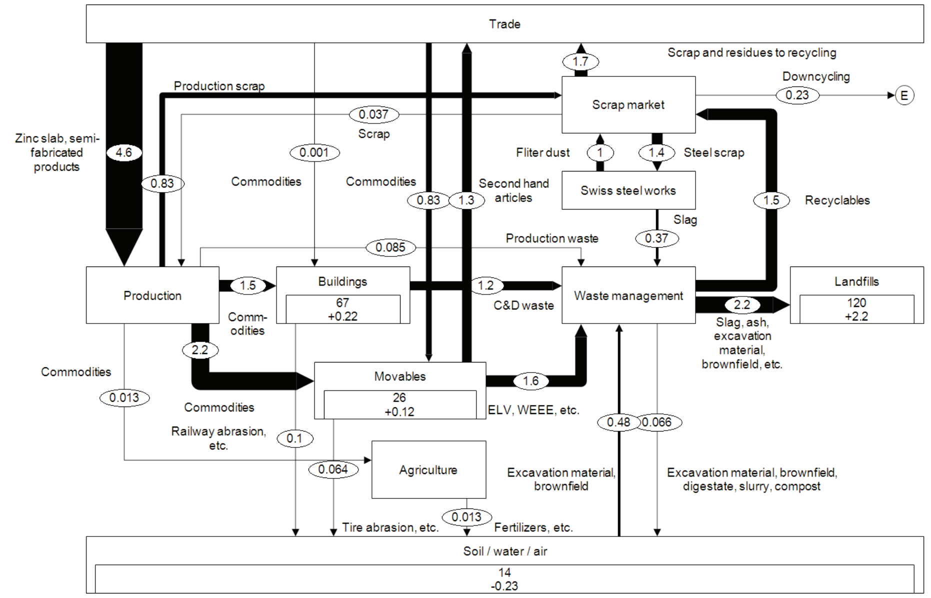


Fig. 3 Zinc flows 2010 (kg/capita/a), stocks 2010 (kg/capita) and stock changes 2010 (kg/capita/a) (based on Hügi et al.[19], Kral et al.[23], Meylan and Reck[24], Schlumberger[31]). The process Waste Management includes municipal solid waste incineration, the acid washing of fly ash, composting and anaerobic digestion, the sorting and treatment of construction & demolition waste and recyclables, etc. (C&D: construction and demolition, ELV: end-of-life vehicles, WEEE: waste electrical and electronic equipment).

7. Society

Some 1'000 businesses are active in the Swiss industrial and metal working machinery and generate about 10% of the gross domestic product.[30] In this sector, zinc is used in batteries and sensors together with critical raw materials, i.e., lithium, nickel, and platinum. Approximately 6'500 persons are employed in metal recycling, including zinc.[43] The steel scrap processors and the two steel works in Gerlafingen and Emmenbrücke also play a role. The 12 Swiss municipal solid waste incinerators recycling zinc by means of the FLUWA and FLUREC processes must be added as well. As of today, FLUWA/FLUREC generates some 27 full time jobs. The industrial solution relying on the FLUWA and SwissZinc processes would mean some 40–50 persons would take care of zinc recycling from fly ash.

The social and cultural aspects of zinc ore mining are increasingly being scrutinized and are analyzed in so called social or socio-economic impact assessments at the opening or closing of mines. Different indicators of social and socio-economic impacts are used (**Tab. 1**). There is still no standardized method for social impact assessment, although the use of such standards has been acknowledged long ago.[21] A standardized method would indeed help compare not only mines on different continents but also primary and secondary production with respect to social and cultural aspects. The comparability between primary and secondary production provides the knowledge base to develop market instruments, such as labels.

The main zinc recycling potential lies in construction and demolition waste, end-of-life vehicles, and refuse (**Fig. 5**). Sorting on the construction or demolition site makes possible the extensive recovery of metals and hence zinc. Besides refuse, more than half of zinc found in end-of-life vehicles ends up in MSWIs as residues from shredders (RESH) after triage and shredding.[23] Some 50% of zinc present in the MSWI input lands in MSWI bottom ash.[25] The possibility of increasing the recycling rate of zinc from MSWI bottom ash should be the object of continuous scrutiny in order to close raw material cycles and create new jobs.

In the midterm, the accumulation of knowledge and technology on acid washing and the treatment of hydroxide sludge or metal recovery by means of hydrometallurgical processes can be exported. The new „Circular Economy Package" conceived by the European Commission and the corresponding adaptation of the Waste Directive[9] should reinforce this trend. The export shares of some Swiss suppliers of waste technologies are already reaching 30 to 40%.[34] To help these providers tap into export markets, the Swiss Association for Environmental Technology (SVUT) is planning to set up an expert platform, which aims to support the implementation of environmental legislation and the commercialization of Swiss environmental technologies in other countries.[34]

Tab. 1 The social impacts considered in two zinc ore mines.[4,8]

Social impacts of a mine opening (South Africa)	Social impacts of a mine closure (Australia)
Macroeconomics (inclusive jobs)	Economic progress (inclusive jobs)
Social aspects and health	Preservation of indigenous culture and traditions
Visual landscapes	Conservation of landscape and environment
Traffic	Social progress and stronger communities
Cultural heritage, archeology, and paleontology	Fulfillment of agreement between indigenous population and other stakeholders

8. Resource management: The overall situation at a glance

Fig. 11 shows the evaluation of zinc's urban mining potential by means of qualitative expert assessment. Its caption and the following text aim at providing the rationale behind the evaluation.

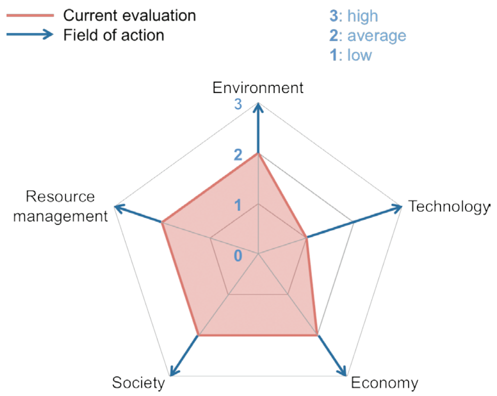
Most uses of zinc are dissipative (c.f. tire wear, for instance), so that measures should be taken in product design.

The private sector promotes recycled steel through its campaign „Öko-Stahl" initiated by „Stahlpromotion", the umbrella organization of the Swiss steel and metal construction industry. „Öko-Stahl" strives for the acceptance of recycled steel in the construction industry. Significant achievements are the public recognition of the real share of recycled steel in steel profiles and the use of ecoinvent data in the Swiss Component Catalogue. The Component Catalogue enables the environmental impact assessment of building constructions. The ecoinvent data do not include avoided environmental burdens through zinc recycling taking place in steel works and improving the overall environmental performance of steel recycling. Including these avoided burdens would make steel recycling even more attractive.

The new Ordinance on Waste Prevention and Disposal (VVEA)[35] prescribes the recovery of metals from MSWI fly ashes. In addition to currently available recovery pathways (Waelz process among others), further technical possibilities and processes (SwissZinc) are developed to contribute to the ecological improvement of the entire system. Around half of zinc contained in the MSWI input ends up in bottom ash. Today, zinc is partially recovered as steel, brass, and zinc alloys from MSWI bottom ash. So far, the FLUWA process cannot treat bottom ash for economic reasons linked to FLUWA's high alkalinity on the one hand, and because of lower zinc concentrations (dilution effect), on the other hand.

Open questions

1. How much zinc from the ferrous and non-ferrous metal fractions (i.e., brass and zinc alloys) in MSWI bottom ash is actually recovered in downstream processes?
2. Which technical solution could enable the recovery of zinc from mechanically treated MSWI bottom ash at acceptable costs?



▶ **Fig. 11** Evaluation of zinc's urban mining potential (all uses) by means of qualitative expert assessment. **Criteria:** *Environment*: Hohe High environmental savings through secondary production, low recycling rates. *Technology:* Improve product design, zinc recovery from mechanically treated MSWI bottom ash. *Economy:* Zinc recovery from hydroxide sludge in development competes with relatively high treatment costs and unstable zinc prices. *Society:* SStandardized methods for the comparison of socio-economic impacts of primary and secondary production are inexistent. Labels would raise awareness on environmental performance. *Resource management:* Need for further development of the technical recyclability of zinc and of the economic framework as well as need for the improvement of product design.

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