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The future availability of zinc: Potential contributions from recycling and necessary ones from mining

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A R T I C L E I N F O

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A B S T R A C T

Society's increasing demand for metals led to the discussion as to whether scarcity of raw materials could lead to supply shortages and to which extend circularity can prevent resource depletion. This study investigates the need for and availability of secondary and primary zinc resources under moderate demand growth. A dynamic MFA model simulates future potentials of 9–14 Mt/a zinc recycling and the necessity of 17–22 Mt/a zinc mining in 2050. The MFA model estimates a cumulative required mine production of 500–560 Mt between 2020 and 2050, which equals less than 1% of the extractable global zinc resources estimated within a geological analysis. With continuous exploration contributing to new discoveries, primary zinc is sufficiently physically available. In contrast, recycling is limited to the amounts of post-consumer waste generation. Recycling capacities need to be extended, collection systems optimized and processing efficiencies increased worldwide to realize the full extent of modelled potentials.

1. Introduction

Society's demand for materials increased heavily in the past (OECD, 2019). Now, Circular Economy actions try to counteract and lower material consumption, aiming to reduce correlated environmental impacts which occur during raw material extraction and material production. Associated strategies are "refuse", "rethink" and "reduce", leading to smarter material usage (Kirchherr et al., 2017). Nevertheless, increasing global population and average prosperity (OECD, 2019) as well as the demand for future technologies needed for the transition towards climate neutrality (Gregoir and van Acker, 2022; Marscheider-Weidemann et al., 2021) are expected to drive increasing global material consumption, especially for metals.

This raises the question as to whether potential depletion of raw materials leads to supply shortages in the future and, in a second step, how recycling contributes to secure the global availability of materials. This study aims to answer these questions for the widely applied base metal zinc. Additionally, this study expands the monitoring of anthropogenic resources, which is according to Leipold et al. (2022) a key factor towards a sustainable Circular Economy. The focus of previously conducted studies found in literature reaches from the metal demand growth (Backman, 2008; Daigo et al., 2014; Elshkaki et al., 2018) to material related emissions (Koning et al., 2018; Watari et al., 2021). Sverdrup et al., (2019), Tokimatsu et al., (2017) and Backman (2008) combine the supply and demand perspective to make conclusions on the depletion of metals. These studies have in common, that they comparatively examine a variety of individual metals. Maung et al., (2019) assess the historic built-up of anthropogenic zinc stocks in six countries. In contrast to these formerly conducted studies, this study focuses on the single metal zinc and increases the depth of detail on both product- and process-level as well as geological background information. The results allow conclusions regarding the future physical global availability of primary and secondary zinc, which is a matter of concern for industry (Fairphone, 2021). Regional aspects like geopolitics, trade relationships or logistics affect the short term supply security of countries, but are out of the scope of the presented study.

We combine material flow analysis (MFA) with a geological analysis, to provide an extensive quantitative basis for the global long term availability assessment for zinc. We analyze future zinc flows following a moderate growth scenario, providing detail on individual applications.

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It is based on historic zinc demand developments as well as projections on population increase and economic growth. This demand scenario drives a comprehensive prospective global MFA model, which is based on an extensive dynamic historical model (Rostek et al., 2022). The model covers the overall anthropogenic zinc cycle until 2050, including mining, production, manufacturing, use phase and waste processing stages. By doing so, we satisfy the requirement for analyzing raw material scarcity as described by Bloodworth and Gunn (2014), namely to investigate the material system as a whole. The model also provides estimates of end-of-life scrap generation based on lifetime distributions of each zinc application. To translate this recycling potential into secondary zinc flows, we developed two recycling scenarios. These vary in technical developments, political ambitions and public awareness. The demand which is not supplied by recycling leads to necessary mining.

A geological analysis is applied to provide up-to-date assumptions for the availability of primary raw material. The assessed parameters include the reserves, known resources, extractable global resources as well as the crustal content. Physical zinc depletion is assessed by comparing the required mining with the known and presumed mineral reserves and resources.

2. Methods and data

2.1. Developing a demand scenario based on historic data

A top-down scenario for future zinc demand up to 2050 is developed. This long term middle-of-the-road scenario is not to be seen as a precise forecast but as one possible future in a likely range, for which the material supply is assessed through analyzing the availability of primary and secondary raw materials. The society's metal consumption is correlating with population size and economic growth (Backman, 2008; Tokimatsu et al., 2017). This holds especially true for base metals such as zinc, which have widely established and multifarious applications in buildings, infrastructure, machinery and transportation. Within these applications, zinc is used in various first use forms: Galvanizing of steel, brass, die casting, chemical compounds and zinc sheets or wire. We analyzed the retrospective correlation of the production of each zinc first use per capita with global gross domestic product (GDP PPP) based on historic production numbers from 2000 to 2019 published by Rostek et al., (2022). A regression analysis was conducted and used to extrapolate the zinc demand per capita (cf. Figure S1). The regression method was individually chosen for each of the first uses to minimize the coefficient of determination by least square method. We applied a background scenario by OECD (2019) for the future development of global population and global GDP (PPP). Within this scenario, the compound annual growth rate of the global GDP is 2.8%. The underlying data can be found in the supporting data excel file.

2.2. Assessing the geological availability of zinc

Exploration geologists report their findings under the generic term of resources with variable degrees of certainty. When well identified resources undergo a more in depth feasibility study (including legal, social, environmental and technical aspects) they might qualify as reserves (CRIRSCO, 2019). In 2021, zinc reserves are estimated to be 250 Mt of Zn (USGS, 2022). Looking back to published reserves of 190 Mt Zn in 2000 (USG, 2000), it is noticeable that over the years, the ratio of reserves to annual production has remained almost constant with a typical secured supply horizon between 15 and 20 years.

To get a better insight into the future, it is important to consider the broader category of resources which represent deposits with variable degrees of knowledge and potentially penalized by socioeconomic uncertainties (lack of social license to operate, high energy cost, low metal prices, etc.). Economic geologists have published extensive databases of both sediment-hosted (SEDEX, MVT) (Leach et al., 2005; Singer et al., 2009; Taylor et al., 2009) and volcanogenic massive sulfides (VMS) (Piercey et al., 2015). Despite huge discrepancies between databases and lack of correspondence in deposit names and spellings, these data, updated by recent statistics from mining companies, do confirm the estimate given by Mudd et al., (2017) of 633 Mt Zn in known resources. Interestingly, this resource is spread over more than 900 inventoried deposits, but more than half of it is concentrated in the hundred largest deposits. The current annual primary production of zinc amounting to 12,8 Mt/a Zn is secured by 340 operating mines, with the hundred largest operations providing more than 80% of it (ILZSG, 2022).

2.3. Modelling approach for prospective zinc stocks and flows

A retrospective dynamic material flow model covering the global zinc cycle published by a part of the authors (Rostek et al., 2022) is extended to include prospective stocks and flows of zinc until 2050. A detailed description of the calculation method of the retrospective model, which quantifies stocks and flows of mining, production, manufacturing, anthropogenic use phase, scrap generation and recycling can be found in the paper by Rostek et al., (2022). The structure of the prospective part of the MFA model and the structure of the presented study is illustrated in Fig. 1 and described in the following. The future production of first use goods as described in Section 2.1 is applied as an exogenous input for the material flow model. The resulting overall demand for zinc is calculated by including the additional need for zinc to produce these products, namely new scrap from first use production or material losses in smelting and refining processes by applying process efficiencies. The calculation of end use manufacturing, new scrap generation, stock building and end of life (EoL) scrap generation is implemented analogous to the retrospective model. After manufacturing, products enter the stock of goods in use where certain lifetime distributions (cf. Table S3) are assigned to them. When reaching the end of their useful lifetime, discarded products can be collected for recycling, indicated by an end-of-life collection rate (EoL CR). In the retrospective model, the EoL-CR is endogenously calculated by applying mass balance, while it is an exogenous parameter in the prospective part of the model. Subsequent processes are the sorting of waste types, the separation of applicable metal fractions and the recycling processes. A linear increase of the efficiency of metallurgical production and manufacturing processes is assumed and summed up in Table S1. Beside the efficiencies, the distribution of zinc used to produce specific end-use products also changes over time, as apparent in historic development (Rostek et al., 2022). Past developments were projected into the future to cover these changes. Two different recycling scenarios are developed, which are described in the following.

The *Recycling as Usual (RU)* scenario hypothesizes in global average unchanging recycling systems including collection, separation and recycling processes. Political inactivity leads to constant efficiencies and collection rates. This means recycling capacity follows scrap availability, but no innovation takes place in the recycling system.

In contrast, the *Recycling Improvement (RI)* scenario assumes significant enhancements in global recycling systems due to technological developments, political endeavors and an increased environmental awareness on global level. The best currently available technology in scrap processing and recycling will be fully established on global scale until 2050 in the RI scenario. The most significant assumptions are: (1) The collection of post-consumer scrap is getting more and more efficient reaching an End of Life collection rate of 61% in 2050 compared to 45% in 2019 (Rostek et al., 2022). (2) There will be a shift from the primary steel route to the secondary steel route, where the recovery of zinc from galvanized steel scrap in the form of Electric Arc Furnace (EAF) dust is more probable. Additionally, within the primary steelmaking route Basic Oxygen Furnace (BOF) dust will not be landfilled or used as filling material anymore, but zinc recovery from these residues will also become standard practice. Conceivable are the enrichment of zinc within the BOF by internal recycling of the dust in the integrated steel work and subsequent recycling via the Waelz process (Sauter, 2022) or

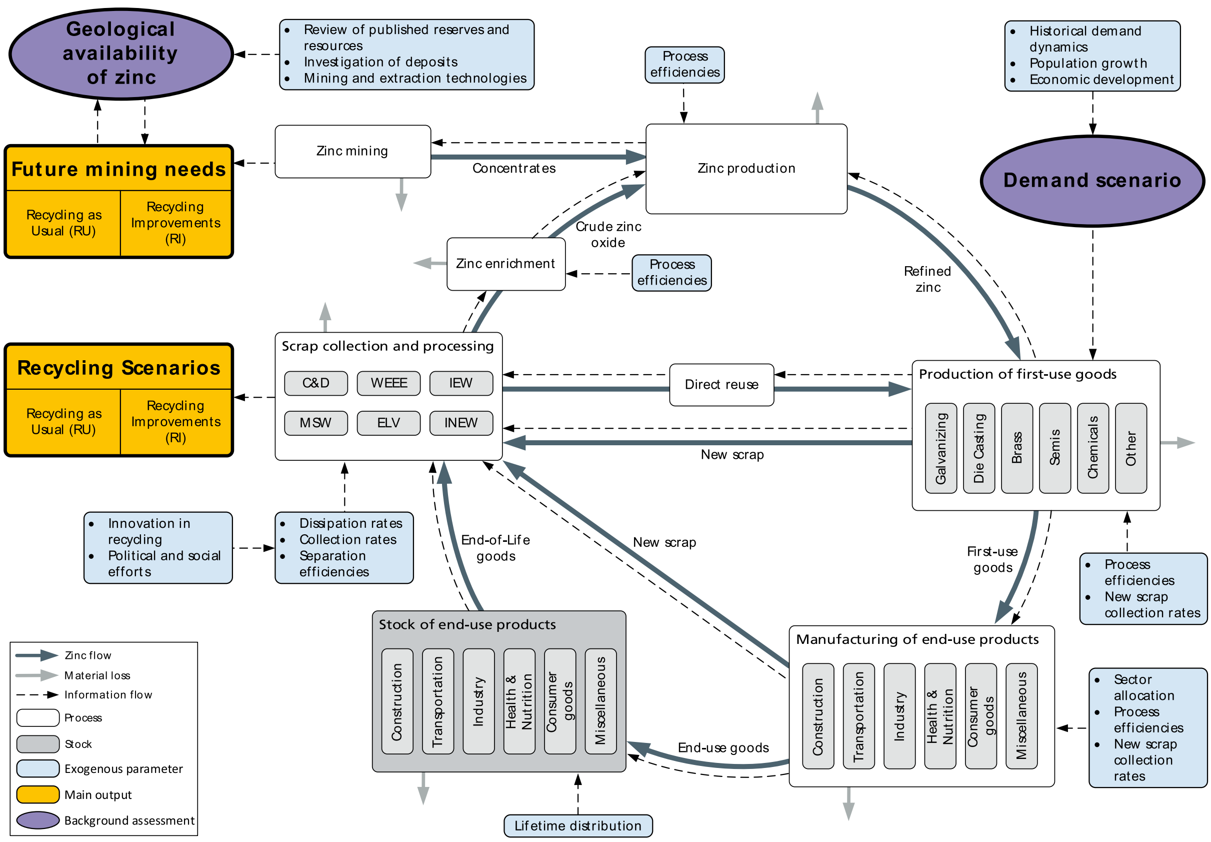

Fig. 1. Schematic structure of the study design and prospective MFA model.

utilization of external recycling processes like the HIsarna process (Strijker, 2020) or the DK process to recycle BOF dusts with zinc concentrations below 15% (Bartusch et al., 2011). (3) Zinc will be recovered from municipal solid waste (MSW) residues. The resulting separation efficiency based on the recovery of zinc from fly ashes (Schlumberger, 2019) and bottom ashes (Bunge, 2018) is assumed to be 64%. All these improvements are estimated to develop linearly until 2050 (cf. Table S2).

The calculation of the recycling and mining flows is different from the retrospective model described by Rostek et al., (2022). The future available scrap for recycling is calculated by summing up the new and old scrap flows and multiplying them with the exogenous applied assumption on the development of the collection rates (cf. Table S2). The respective collected scrap flows are multiplied with associated separation efficiencies and recycling process efficiencies depending on waste composition and recycling scenario. The actual short term demand for zinc affecting zinc prices and stocking or destocking of raw materials and scraps was neglected when calculating the recycling flows. The future requisite zinc mining to supply the applied zinc consumption is calculated by balancing the total demand and the calculated secondary zinc supply, taking additional upstream material losses from refinery and Waelz process into account. Both recycling scenarios are based on the same demand scenario, while the RU scenario can be seen as the future with least recycling and most mining and the RI scenario as optimal recycling and minimum mining.

3. Results and discussion

3.1. Zinc demand scenario

Zinc demand can be seen as the required material to maintain and expand the anthropogenic stock of goods to fulfill society's needs for service-providing goods. Following the method described in Section 2.1, the demand for zinc in first use products is estimated to increase from 17.5 Mt/a in 2019 to 28 Mt/a in 2050. Fig. 2 gives the development of first uses production over time, where data by Rostek et al., (2022) are used for the retrospective timespan until 2019 and the method described

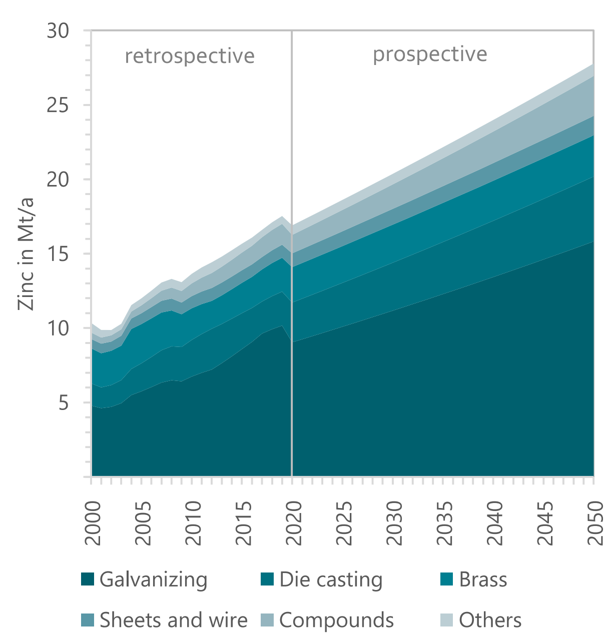

Fig. 2. First use production until 2050 according to a regression analysis as a basis for the zinc demand scenario. Historical data up to 2019 based on Rostek et al., (2022). See supporting data for underlying numbers.

in Section 2.1 to project the demand from 2020 onwards into the future. The detailed dataset can be found in the supporting data excel file.

Seven former studies indicate a global overall zinc demand in 2050 between 14.5 Mt/a and 38.8 Mt/a with an average of 26 Mt/a (Backman, 2008; Elshkaki et al., 2018; Gregoir and van Acker, 2022; Koning et al., 2018; Sverdrup et al., 2019; Tokimatsu et al., 2017; Watari et al., 2021; Watari and Yokoi, 2021). While the actual zinc demand in 2050 necessarily remains unknown, the demand scenario shown in Fig. 2 fits well within the range of expectations for future zinc demand found in the literature (cf. Figure S2). An advantage of this method is that the breakdown of first uses develops independently into the future, while other scenarios extrapolate total demand (Backman, 2008; Elshkaki et al., 2018; Koning et al., 2018; Sverdrup et al., 2019; Tokimatsu et al., 2017; Watari et al., 2021; Watari and Yokoi, 2021). This allows the tracking of shifts within the first use structure, which are relevant for the lifetime and efficiency assumptions within the MFA model. Through 2050, the scenario considers a slightly increased share of zinc used to produce chemical compounds (10% in 2050) and die castings (16% in 2050) at the expense of mostly brass (10% in 2050). Galvanizing of steel remains the most important application for zinc and is estimated to be almost stable with a share of around 57%.

In addition to the ongoing developments within zinc consumption and its correlation to economic and population growth, additional effects can have a significant influence on zinc demand. The methodology described in Section 2.1 projects the current trends into the future and neglects disruptive events in the applications of zinc, which could emerge through innovation or substitution. Such an emerging technology could be rechargeable zinc batteries (Li et al., 2019). However, they still need substantial development to reach market maturity (Shi et al., 2020). Current scenarios for their application until 2050 do not show amounts relevant to this demand scenario (Daniel-Ivad and van Leeuwen, 2022). To the best of our knowledge, no further emerging technologies or substitution trends with a possible significant impact on zinc demand are foreseeable. Therefore, the demand scenario focuses on the common and widely applied uses of zinc.

Besides technological aspects, political action leading to behavioral or structural changes can impact the global zinc demand. An extensive and global implementation of circular economy could lead to a lower zinc demand due to lifetime extension measures like reuse, repair, refurbishment or remanufacturing, as well as a more extensive implementation of sharing concepts leading to a higher intensity of use for certain products. A significant change in global average speed of renewable energy expansion would also influence the amount of zinc used in respective technologies like wind energy plants or power grids. In summary, political and technological factors are considered in so far as there is a continuation of current trends, while disruptive changes and their impact on zinc demand are not subject matter of this study.

3.2. *Very long-term availability of primary resources*

Modern geologists have a very good understanding of how zinc is rather homogeneously distributed among all types of rocks in the Earth crust with an average concentration of 70 ppm (Rudnick and Gao, 2003). They also understand quite well how concentration processes are active in the current environment and how they have been operating similarly in the past 2.5 billion years (Huston et al., 2006). Based on this, the potential for finding Pb-Zn sulfide deposits or metal-rich brines at much greater depths is well established and it makes no doubt that extensive exploration would reveal much more resources. A vast majority of the currently mined deposits were identified with very simple exploration techniques and even by laymen. Most of them crop out within the first 300 m of the crust and only very few deeper discoveries have been made incidentally (e.g. Admiral Bay at -1250 m) when drilling for oil.

A study on the undiscovered resources in the US (USGS, 2000), suggested that resources until a depth of 1 km could typically amount to 4.82 times the currently known resources. Considering that the US only represents 1:21 of the total continental crust surface, it is reasonable to extrapolate the potential for resources within the entire continental crust. Table 1 illustrates two different scenarios considering the optimistic hypothesis that about one third (1/3) of the crust has been explored to the same extent as the US territory and down to a depth of 1 km. For the rest of the world (2/3), a more plausible hypothesis is to consider these territories are underexplored relative to the US by a factor of two and the known zinc deposits are all within the first 330 m. An alternative scenario considers the very pessimistic hypothesis that exploration already went down to 1000 m.

Under the assumption that a 5 km mining depth is technically possible, especially with the development of remote controlled and unmanned operations, this would amount to a total of Extractable Global Resources (EGR) ranging from a very conservative 25 Gt Zn to a more realistic estimate of 67 Gt Zn. Referring to the database by Mudd et al., (2017), this means that the world zinc resources (633 Mt Zn) discovered so far only represent 0.95% – 2.49% of the Extractable Global Resources. Considering an acceptable significant increase of the price of zinc in the upcoming centuries, it makes no doubt that even more resources could be unlocked at grades well beyond the ones being considered today in the estimation of resources. In all possible scenarios, the numbers above are in huge contrast to the numbers published by Henckens et al., (2016) advocating that 1.9 Gt out of a total of 2.8 Gt extractable global resources of zinc have already been found, putting zinc in the top five list of the scarcest elements on Earth and claiming that total exhaustion will happen a few decades after 2050. Henckens et al., (2016) use a largely overestimated tonnage for discovered resources which does not correspond to the extensive world databases reviewed in this paper. Most importantly, they use an EGR estimate from UNEP (2011) corresponding to 0.01% of a crustal content estimated to be as low as 28 Tt Zn down to the first kilometer only.

Based on the same, widely accepted, average content of 70 ppm Zn in the total continental crust (Rudnick and Gao, 2003), on an average density of 2.7×10^3 kg/m^3 and on the most accurate estimate of the area of the continental crust (210.4×10^6 km^2) given by Cogley (1984), we can estimate the crustal content of zinc limited to a depth of five kilometers. The amount of zinc per km^3 of continental crust is:

$$2.7 \cdot 10^3 \frac{kg}{m^3} * 70 \cdot 10^{-6} \frac{g\ Zn}{t} = 189 \cdot 10^3 \frac{t\ Zn}{km^3}$$

Hence the total amount of zinc in the continental crust over a thickness of 5 km is given by:

$$189 \cdot 10^3 \frac{t\ Zn}{km^3} * 210.4 \cdot 10^6 km^2 * 5km = 198\ Tt\ Zn$$

The ratio of EGR to crustal content is unknown and highly speculative. In his seminal paper warning on the existence of a so-called mineralogical barrier, Skinner (1976) places a limit at ten times the energy required today to extract a metal from its ores. He adds a rough guess that it could be between 0.01% and 0.001% but provides no substantial arguments to his guess, as this region of intermediate grades between 70 ppm and 3% is, by definition very poorly known and most often not reported by geologists. Our estimate of extractable global zinc resources of 67 Gt Zn represents 0.034% of the total crustal content within the first five kilometers (198 Tt Zn), as visualized in Fig. 3. This seems very realistic for a widely distributed and mobile base metal such as zinc and certainly not in contradiction with Skinner's ideas even though being on the optimistic side.

3.3. *Availability of secondary raw material*

Besides primary raw materials, several secondary raw materials such as zinc containing scrap, waste, ashes, slags and residues can contribute to meet zinc demand via recycling processes. Antrekowitsch et al., (2014) and Martens (2011) describe various zinc recycling processes,

Table 1
Estimation of undiscovered zinc resources in the Earth crust based on two different scenarios of current exploration depths (330 m and 1000 m). Estimates are based on discovery factors comparable to the US territory (USGS, 2000) for one third of the crust, the rest being considered as twice less explored.

	Known resources [Gt Zn]	Estimated exploration depth [m]	Discovery factor [-]	Undiscovered resources @ 1 km [Gt Zn]	Undiscovered resources @ 5 km [Gt Zn]
US-like Exploration Coverage (1/3 of continental crust)	0.211	1000	4.82	1	5
Non US-like Exploration Coverage (2/3 of continental crust)	0.422	330	4.82×2	12	62
		1000	4.82×2	4	20

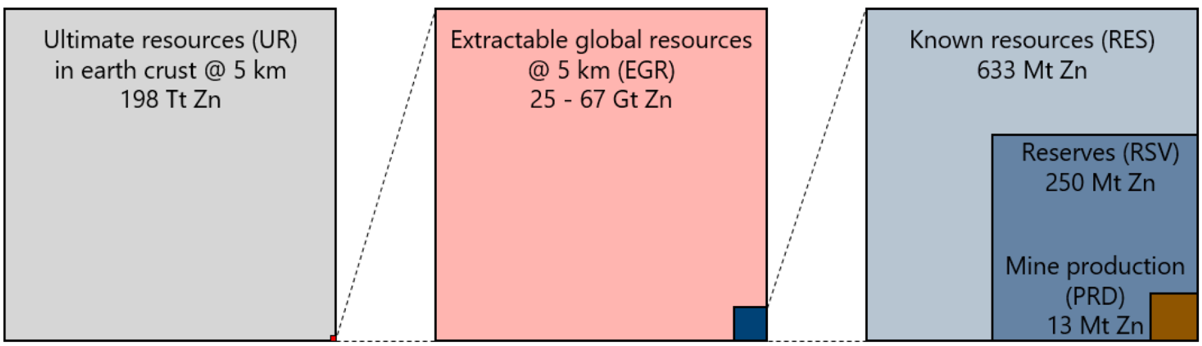

Fig. 3. Quantification of mineral zinc resources. Quantification of RES by Mudd et al., (2017), of RSV by USGS (2022) and of PRD by (ILZSG, 2022).

while van Leeuwen et al. (2021) provide an overview of recycling pathways and their embedment in the zinc cycle. Within this study, an assessment of the future availability of secondary raw materials is conducted by applying a prospective dynamic MFA. Potential secondary sources are new scrap from both first use production and end use manufacturing as well as post-consumer goods leaving the stock of goods in use due to the end of their useful lifetime, the latter being called old scrap in the following paragraphs.

The development of scrap generation by origin is shown in Fig. 4 and given in the supporting data file. These flows are the theoretical potential for secondary raw materials, while dissipation, collection, separation and recycling losses reduce the recycling potential in practice. The new scrap generation from the production of first uses and manufacturing of end uses increases moderately from 2.3 Mt/a and 1.7 Mt/a in 2019 to 3.0 Mt/a and 2.6 Mt/a in 2050. Due to the increasing demand for zinc and the considerable long lifetime of zinc especially in

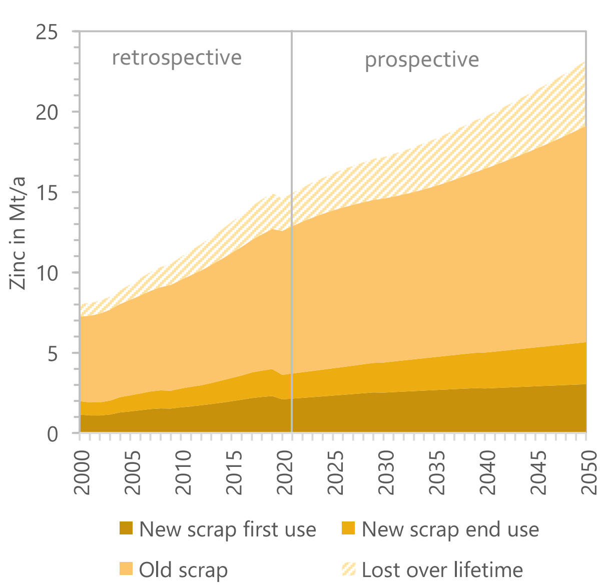

Fig. 4. Generation of scrap by origin. Historical data up to 2019 based on Rostek et al., (2022). See supporting data for underlying numbers.

galvanized products, the stock of zinc in use keeps growing and reaches 491 Mt in 2050 compared to 247 Mt in 2019 (cf. Figure S3). In both growth and size the building and infrastructure sector is the largest application category accounting for 46% of overall zinc in use in 2050. The stock outflow (EoL scrap) increases from 10.9 Mt/a in 2019 to 17.5 Mt/a in 2050. Not all zinc material leaving the use phase becomes available for recovery. Material losses arise within the use phase by applications being inherently dissipative as well as by corrosion, abrasion or products being abandoned in place and therefore not practically collectable. Of stock outflow, 80% were theoretically collectable in 2019, while 2050 77% or 13.4 Mt/a are collectable for recycling, which comes from slight shifts within the end use distribution. Consequently, 19.1 Mt/a of zinc is potentially collectable for recycling from new and old scrap in 2050.

Besides these secondary raw materials, landfills and tailings can be sources for zinc production. Due to the relatively low zinc price and the highly challenging process of zinc recovery from these sources, landfill mining is neglected as secondary raw material.

3.4. Implications for supply

Zinc supply can be differentiated into primary and secondary supply. Two scenarios until 2050 are developed, which are based on the same overall demand (cf. Section 3.1) but differ in the amount of zinc from recycling. Fig. 5 shows the zinc supply from both mining and recycling. The underlying data is provided in the supporting data file. The actual future supply under the presumed demand scenario is believed to lie in-between both extreme scenarios. The RI scenario gives the maximum recycling and minimum mining, while the RU scenario represents the opposite case. We estimate the old scrap collection to increase to 7.7–10.7 Mt/a of zinc per year in 2050. Due to separation losses and process losses this amount reduces to 4.8–9.1 Mt/a of zinc in 2050. The separated material is applicable for zinc metal production or production of zinc containing goods. With significant but reachable improvements in collection and recycling, the waste processing losses could decline from 2023 onwards, even though production numbers and scrap generation increase. The recycling of new scrap is estimated to increase steadily to 4.6–5.2 Mt/a in 2050. Overall, zinc recycling increases from 6.2 Mt/a in 2019 to 9.3–14.3 Mt/a in 2050 (Fig. 5), showing a growth rate which is constant or even increasing. As a consequence, an

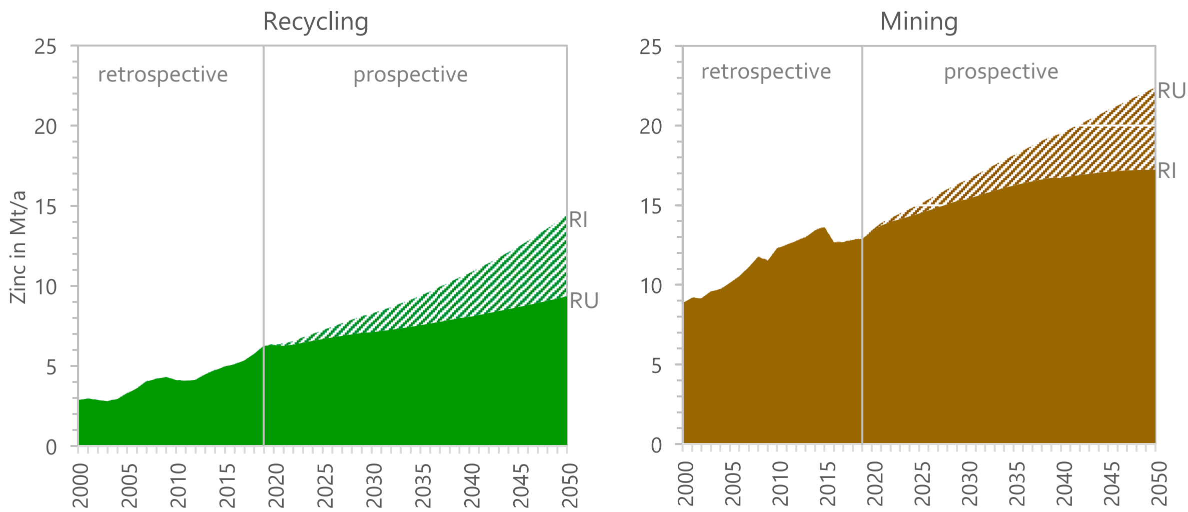

Fig. 5. Zinc supply from recycling (left) and mining (right). Striped area equals the difference of the RU and RI scenario, while e.g. the maximum recycling consequences the minimum mining. Historical data up to 2019 based on Rostek et al., (2022). See supporting data for underlying numbers.

extension of the current global zinc recycling capacity is indispensable even in the RU scenario. Besides the recycling capacity increase, the RI scenario presupposes global operating and substantial enhancement of recycling systems such as a more intense use of steelmaking dusts, zinc recovery from municipal solid waste and improvements of post-consumer scrap collection. The maximum potential for zinc recycling is clearly defined through the availability of secondary raw materials (cf. Section 3.3). Even in the RI scenario, this potential will not be fully exploited because of incomplete collection and unavoidable losses defined by thermodynamics (Reuter et al., 2013).

Even with strong improvements in collection and processing, secondary raw materials cannot provide enough zinc to fulfill the projected demand. Material not available from recycling will have to come from primary sources. To fulfill the applied global demand, 17.2–22.3 Mt/a of zinc will have to be mined in 2050 (Fig. 5). Under the RU scenario, the growth of zinc mining from 2020 to 2050 needs to be nearly constant, while it slows down in the RI scenario and reaches a saddle point at around 2050. The recycling input rate gives the share of recycling in the overall zinc supply and is estimated to reach 29% in the RU and 45% in the RI scenario in 2050. Compared to that, the estimations for the recycling input rates for the same year in literature have a similar scale and lie between 34% (Watari and Yokoi, 2021) and 51% (Sverdrup et al., 2019).

As present in Fig. 5, mining is expected to grow between 2020 and 2050 by 140–182%. In comparison, zinc mine production grew by 172% in same length of time between 1990 and 2020 (ILZSG, 2022). Continuation of mining capacity growth at a historical pace does not seem to be a bottleneck for future primary zinc production. Cumulatively, the scenario gives an amount of 500–560 Mt of zinc mining between 2020 and 2050. Due to its dynamic characteristic, the current reserve is not appropriate for indicating the long term availability of mineral raw materials. In the case of zinc, the estimated mining between 2020 and 2050 doubles the current reserves of 250 Mt (USGS, 2022). In reality, this should not be a concerning fact, as both reserves and currently known resources are dynamic. Deposits being present-day resources can shift to reserves and the detection of unknown resources can expand the known resources. This continuous process led to increasing zinc reserves between 2000 and 2021 alongside the mine production (USGS, 2022). As mining growth rate is not expected to increase, also the growth of addition to reserves can remain at the historical level. Currently, 39% of the known resources are reserves and 1% of the estimated EGR are known resources. The cumulative mining from 2020 to 2050 corresponds to not even 1% of the potential resources represented by the EGR. Actions needed to extend reserves and known resources are exploration, technological developments like remote controlled extraction to increase the mining depth, as well as licensing and reprocessing mine tailings. Beside these, the profitability of mining, which is affected by zinc prices and mining costs, has a considerable influence on the expansion of mining capacities. The by-product recovery of e.g. precious metals, indium or germanium from zinc mining could additionally influence its profitability (Notom et al., 2022). Under the reasonable assumption that half of the currently known resources will turn into reserves and that exploration will contribute new discoveries, it makes no doubt that the cumulative 500–560 Mt Zn needed until 2050 will be physically available. This makes a mineral depletion of zinc to appear unsubstantiated.

4. Conclusion

The long-term availability of zinc has been questioned in the past (Henckens et al., 2014). The herein presented study applies a demand scenario and two recycling scenarios within a prospective dynamic model covering the global zinc stocks and flows of the entire anthropogenic cycle up to 2050 and analyzes the geological presence of zinc ores. The outcome concludes, that zinc resources in the form of primary and secondary raw materials are sufficiently available to supply the projected demand up to 2050. Even in the very long term future past 2050 a depletion of zinc resources is not foreseeable due to the high expected extractable global resources of 25–67 Gt of Zn. Following this, the mere presence of raw materials will not be a limiting factor for the zinc supply security. Nevertheless, there is an uncertainty in short or middle term, which is linked to geopolitical instabilities, lack of social license to operate and possibly underspending in exploration (Schodde, 2017).

The model-based scenario analysis shows that primary supply will need to exceed secondary supply and continuously grow in amount of zinc provided over the whole period of time up to 2050. This emphasizes the ongoing significance of primary production. Nevertheless, mining is accompanied by social and environmental burdens (UNEP, 2013). It inherently contradicts the principle of sustainability. It must be questioned whether the required mine production can be exploited while respecting social and environmental limits. Mining activities come with high land use as well as water and air pollution affecting local ecosystems and biodiversity (Luckeneder et al., 2021; Northey et al., 2017). As a consequence, social conflicts with local population can arise. This emphasizes the importance of a transition towards more responsible mining practices.

Secondary production has the ability to reduce the necessary mining activities and their associated environmental and social constraints. Additionally, circularity contributes to long term availability and is a major factor for raw materials supply security on global and especially on regional level for non-extracting countries. However, the availability of secondary raw materials is limited due to long-living products, dissipation over lifetime and incomplete recycling systems. A growing material demand cannot be supplied from recycling alone because more material is needed than was fed into the system in previous years.

The herein developed model-based recycling scenarios show a significant potential contribution from recycling if the necessary effort is put into development of the recycling system. In the more conservative scenario (RU), overall processing stays as it is today but global recycling capacities need to be continuously extended to keep up with the growing scrap generation. This way 9.3 Mt/a of zinc can be provided by recycling in 2050 enabling a recycling input rate of 29% (cf. Rostek et al., (2022) for definition). An extensive and global effort in improving the overall recycling system could lead to recycling amounts catching up to 14.3 Mt/a compared to 17.2 Mt/a of primary zinc supply, leading to a recycling input rate of 45% according to the optimistic scenario. To achieve this, post-consumer scrap collection would need to be significantly more effective than today at a global scale, the recycling of zinc from steelmaking dusts would need to be extended to both furnace types and lower quality residues and municipal solid waste would need to be utilized for zinc recovery.

The first principle for long term availability of zinc is the conservation of resources. Following, the decrease of the overall zinc demand must be in focus. The herein applied zinc demand scenario has to be seen as a middle-of-the-road scenario, expecting a moderate growth due to continuation of current trends. Circular Economy strategies go beyond the expansion of recycling discussed here. They also include measures to use products smarter and extend the lifespan of products and its parts (Kirchherr et al., 2017) as well as to use less products. These efficiency and sufficiency strategies have the ability to reduce the material demand projected here, which is the most efficient measure to meet the carbon emission targets (Watari et al., 2020; Watari et al., 2021). A lower zinc demand reduces primarily the amount of zinc needed to be mined, if secondary resources are preferably used. Therefore, decreasing the overall zinc demand is the most effective instrument to further ensure the long term availability and additionally leads directly to less environmental impacts connected to metal production.

CRediT authorship contribution statement

Leon Rostek: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Eric Pirard:** Formal analysis, Investigation, Project administration, Writing – original draft. **Antonia Loibl:** Supervision, Conceptualization, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Leon Rostek reports financial support was provided by International Zinc Association. Eric Pirard reports financial support was provided by International Zinc Association.

Data availability

Data will be made available on request.

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Supplementary materials

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