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The Circular Economy in Terms of Zinc Recovery from Industrial Waste – Directions for the Development and Profitability of Recycling

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Abstract

The article reviews the current state of the art in the field of zinc recycling. The results of model studies of the profitability (profitability) of the process of zinc recovery in precipitation in the form of dusts and sludges are presented. The cost of purchasing waste and the necessary energy and material expenditures were taken into account. It has been shown that access to a cheap source of waste is essential for the profitability of the zinc recovery process.

Keywords:

circular economy, industrial waste, recycling, zinc recovery, zinc dust, profitability of recycling process

1. INTRODUCTION

According to data [1, 2], the global annual production of zinc is over 13 million tons. Another source [3] states that the estimated global production of metallic zinc in 2007 was 11.4 million tons. Most of this, about 55% [4, 5], is used as a material for corrosion protection by galvanizing the surface. The remaining part is used for the production of alloys with other metals: brass and bronze alloys (about 20%), zinc alloys (13%) and other chemical materials (10%) [4]. Figure 1 shows the global consumption of zinc in various economic sectors.

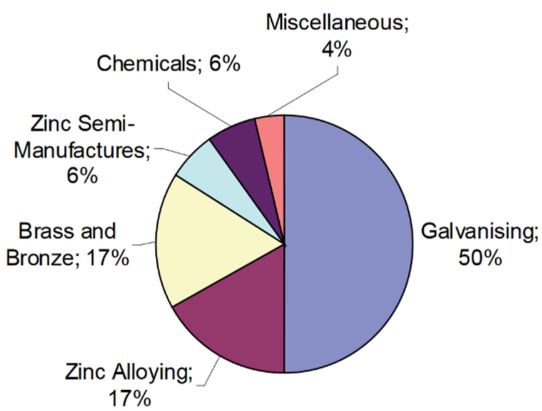


Fig. 1. Percentage share of zinc consumption depending on the sector of the economy, in the world perspective [5, 6]

The use of zinc as an anti-corrosion agent worldwide increased from 10.9 million tons in 2009 to 13.0 million tons in 2013 [5]. The authors [7] assume that at the current rate of consumption, the demand for zinc by 2050 will be 2.7 times higher than today. The main source of primary zinc are sulfide ores, containing from 2 to 30% of zinc, from which the so-called concentrates through the froth flotation process. Pure, metallic zinc is obtained via pyrometallurgical or hydrometallurgical processes [3, 8]. Figure 2 shows the technological operations of zinc production by hydrometallurgical and pyrometallurgical methods.

According to calculations, for the production of 1 kg of zinc from primary sources (from ore: copper, lead, zinc, silver, gold), which contains 62% of zinc, it is necessary to use resources that amount to the emission of 10.64 million tons of CO_2 per year or 0.03% of global CO_2 emissions [7]. In order to achieve climate goals, measures must be taken to reduce carbon dioxide emissions. One of the ways that can contribute to their achievement seems to be the secondary recovery of zinc from industrial waste – recycling. Thus, by meeting the main assumptions of the circular economy, the consumption of natural resources and environmental degradation are reduced, and at the same time the by-products generated in other areas of the economy are managed. In [9, 10], a sustainable circular economy is defined as a transformation in which the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimized [9, 11]. At the same time, efforts should be made to replace the linear economy, a diagram of which is shown in Figure 3, and to apply the assumptions of the circular economy as widely as possible (Fig. 4), bringing both environmental and economic benefits.

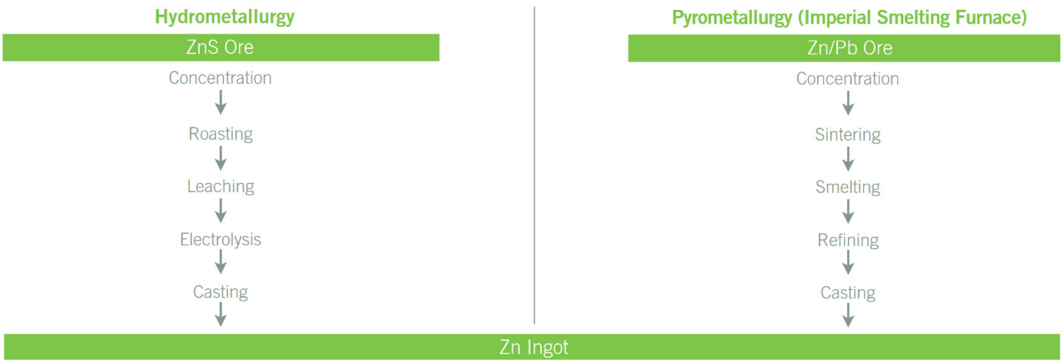


Fig. 2. Scheme of the hydrometallurgical and pyrometallurgical zinc production process [3]

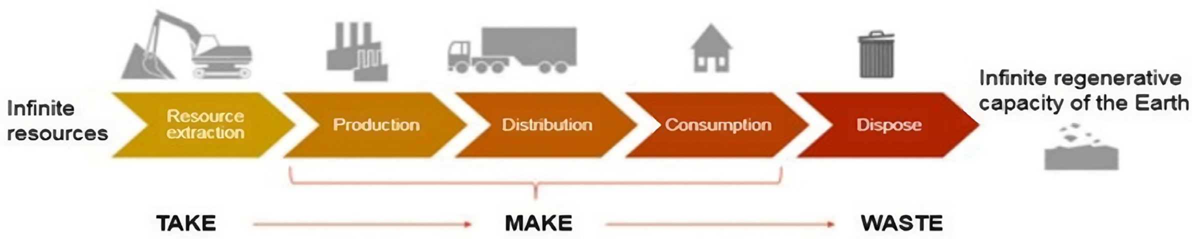


Fig. 3. Linear economy scheme [12]

Fig. 4. Diagram of the circular economy [13]

Some of the short and long term benefits of recycling and reusing mining and metal mining waste include [9, 11]:

- creation of financial assets,
- increasing resource efficiency by limiting the linear consumption of natural resources,
- limiting the production and collection of waste,
- encouraging innovation and development of local spin-offs,
- job creation,
- shared responsibility and ownership over the environment.

Zinc-containing waste is not only scrap such as castings. Significant amounts of zinc are found on anti-corrosive steel sheets that are recycled. During this process (smelting) the zinc evaporates and deposits in the form of dust on the filters. The current possibilities of recovering valuable raw materials and the desire to minimize the amount of waste make zinc-containing dusts and sludges a valuable source of this element and an alternative to obtaining it from primary sources. According to [14], in the European Union alone, in 2018, 74 Mt of crude steel was produced in electric arc furnaces, at 2/3 of the total production capacity. Assuming the production of 17 kg/t of EAF steel per year, 1.26 Mt of EAF steel dust is generated, typically containing from 15% to 40% zinc. With a European recycling capacity of 1.1 Mt, most of the zinc in EAF dust is now recycled in the EU, while globally around 60% of EAF dust currently ends up in landfills. The dominant process used to smelt recycled materials with a high content of zinc is the Waelz rotary kiln, where the zinc is first reduced, then re-oxidized and recovered as impure zinc oxide containing 50–60% zinc [4]. A significant disadvantage of the pyrometallurgical method is the high energy demand, but also the need to use process gas purification systems. An additional problem of a technological nature are chloride and fluoride salts, which are characterized by a high corrosion potential. In turn, hydrometallurgical recycling methods allow for the processing of waste with a low content of zinc and are more environmentally friendly [8].

Figure 5 shows a comparison of energy consumption during individual zinc recovery processes by hydrometallurgy and pyrometallurgy, and Figure 6 shows the carbon footprint (carbon dioxide emission) per ton of zinc produced.

Based on data from Eurometaux (European non-ferrous metals association) and the Institute of Scrap Recycling Industries (ISRI), the energy demand for zinc recovery from waste and the associated carbon footprint were estimated (Table 1).

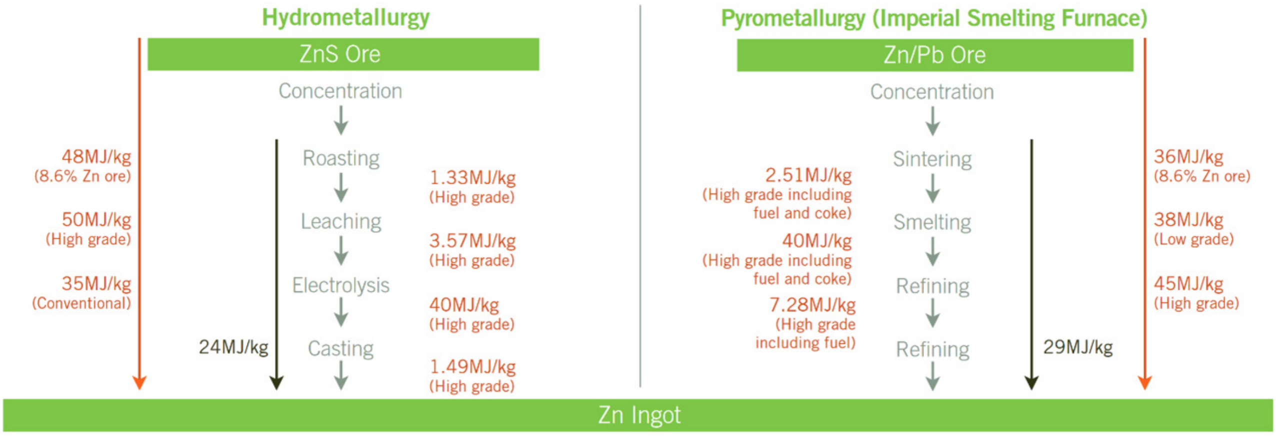


Fig. 5. Energy consumption in the process of zinc recovery by hydrometallurgy and pyrometallurgy [3]

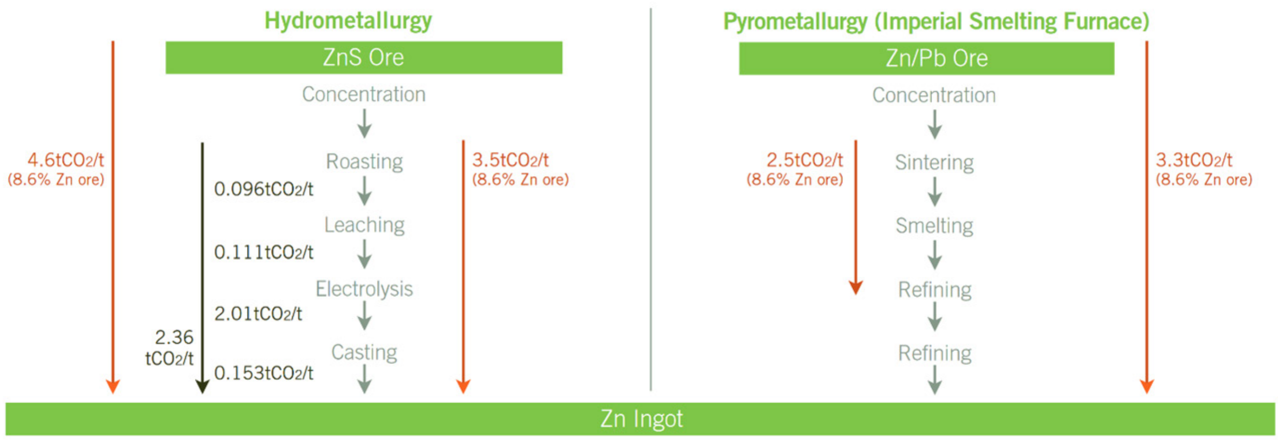


Fig. 6. Carbon footprint related to the hydrometallurgy and pyrometallurgy process [3]

Table 1
Energy demand for zinc recovery from waste (secondary metallurgy) and the associated carbon footprint. Own elaboration based on [3]

Process	Energy requirements			Carbon footprint [t CO_2/t Zn]
	energy requirement [MJ/kg Zn]	electricity [%]	additional	
Dezincing	54	–	–	4.6
Waelz-kiln process	18	93	1.2 t coke/t Zn	0.7–1.4
EZINEX	35	82	–	
DC-furnace	27	96	0.2 t coke/t Zn	

Table 2
Comparison of energy consumption (TJ)/100,000 tons for primary and secondary production of different types of metals [3]

Material	Primary	Secondary	Saving/100,000 tons
Aluminium	4700	240	4460
Copper	1690	630	1360
Ferrous	1400	1170	230
Lead	1000	13	987
Nickel	2064	186	1878
Tn	1820	20	1800
Zinc	2400	1800	600
Paper	3520	1880	1640

Table 3
Comparison of carbon footprint (100,00 t CO_2)/100,000 tons for the primary and secondary production of various types of metals [3]

Material	Primary	Secondary	Saving/100,000 tons
Aluminium	383	29	354
Copper	125	44	81
Ferrous	167	70	97
Lead	163	2	161
Nickel	212	22	190
Tn	218	3	215
Zinc	236	56	180
Paper	0.17	0.14	0.03

Tables 2 and 3, on the other hand, show that the zinc recycling process is both more economical, but also leaves a smaller carbon footprint compared to primary metallurgy. In terms of energy demand, the Waelz overburden process is particularly advantageous, but it requires the use of additional material in the form of coke, necessary for the reduction of zinc oxide. The report [3] clearly shows that per 100,000 tons of zinc, the energy demand for primary zinc production is 2400 TJ, and in the recycling process (secondary metallurgy) 1800 TJ, and the carbon footprint: 236,000 t CO_2 and 56,000 t CO_2, respectively.

Zinc-containing sludges are another source of zinc. At the ZGH "Bolesław" plant, they are subjected to a flotation process in order to obtain a Zn-Pb concentrate with an increased silver content. As a result of the sludge enrichment process, a Zn-Pb-Ag concentrate (and by-products) is obtained, which, after thickening, is sent for recovery in the Waelz overburden process, enabling the recovery of zinc and lead [15]. Currently, apart from the Waelz process, the Primus technique is used in Europe to recover zinc from dust with a higher content of zinc. In the case of waste containing smaller amounts of zinc, the DK, OxyCup and RedIron processes are used [5].

2. DESCRIPTION OF THE TECHNOLOGY USED TO ASSESS THE PROFITABILITY OF ZINC RECOVERY FROM DUST

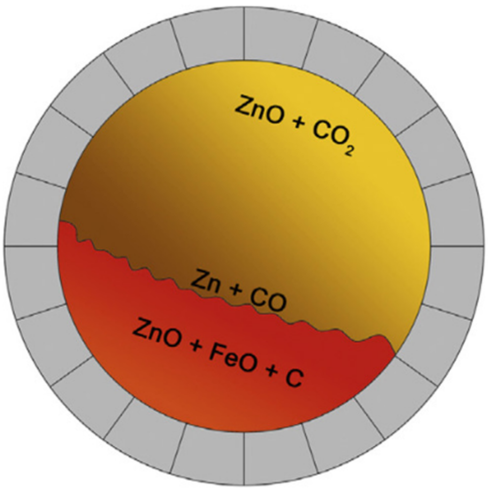
The technology used for the tested model is based on the parallel processing of two zinc-containing waste materials, which are separated due to their chemical composition and semi-finished products (concentrates). The first group includes sludges from zinc hydrometallurgy, sludges from industrial wastewater treatment plants, sludges from acidic wastewater treatment plants and others. The second category of waste consists of steelmaking dusts generated during the melting of galvanized steel scrap in electric furnaces.

As a result of processing sludges containing approx. 12% zinc and 5% lead, a product is obtained in the form of granulated zinc concentrate with increased metal content, i.e. approx. 43–45% zinc and approx. 12–16% lead. As a result of the transformation of steelmaking dusts containing approx. 15–35% zinc and approx. 2–4% lead, a product is obtained in the form of a zinc concentrate with an increased content of metals up to approx. 65% zinc, in the case of lead approx. 4–6%. The process of waste processing and zinc recovery is carried out in rotary kilns. Their processing is a multi-stage process, which consists of a batch preparation stage, waste processing in rotary kilns (metallurgical process), a stage of processing the produced concentrate into the physical form required by the consumer, i.e. granulation of the zinc sludge obtained in the process of processing sludge from hydrometallurgy or the preparation of an aqueous suspension in the case of a concentrate obtained from the treatment of steelmaking dusts.

In the process of sludge processing, an additive regulating the so-called alkalinity module of the charge, which is quartz sand. In the case of processing dusts and sludges, it is necessary to introduce a reducer in the form of coke breeze or fine-grained anthracite. The consumption of the reducer is from 25% to 40% by weight compared to the dry weight of the zinc-bearing material. The materials prepared and mixed in this way are introduced into the working space of the furnace. The movement of the charge is possible thanks to the appropriate inclination of the furnace and its rotational movement. The gases generated during the process move through the kiln in a counter-current to the charge, and their movement is possible thanks to the operation of the suction fan located behind the kiln. In the first stage, water is removed, and in the next stage, chemical compounds are decomposed.

Reduction of zinc oxide with coke breeze at high temperatures causes the zinc to evaporate and then re-oxidize. In the last zone of the furnace, slag is formed as a by-product of the process. At a temperature of 600–800°C, the slag leaves the furnace under the influence of gravity, and then, after being cooled with water, it is collected by a scraper conveyor and stored. Zinc oxide is captured in the devices of the cooling and dedusting installation, such as the dust chamber, exchange cooler, bag filter of intensive dedusting. Dusts from the bag filter contain the highest amount of zinc, with the least deposited in exchange coolers. Zinc concentrate is a product of the zinc filter dust process.

During the processing of steelmaking dusts, the zinc concentrate in the form of dust or water suspension is transported for further processing in the hydrometallurgical process. The zinc-lead concentrate extracted from the sludges is exposed to granulation in a drum granulator. The product of granulation is zinc-lead concentrate granulate, the subsequent processing of which enables the recovery of metallic zinc and lead – in a different pyrometallurgical process. Figure 7 shows the main reactions taking place in the Waelz collapse process.



Reactions in gas phase (oxidizing)

$Zn + ½\,O_2 \rightarrow ZnO$
$CO + ½\,O_2 \rightarrow CO_2$
$Zn + CO + O_2 \rightarrow ZnO + CO_2$

Escaping CO gas and Zn vapor

Reactions in the charge (reducing)

$ZnO + CO \rightarrow Zn + CO_2$	$FeO + CO \rightarrow Fe + CO_2$
$CO_2 + C \rightarrow 2\,CO$	$CO_2 + C \rightarrow 2\,CO$
$ZnO + C \rightarrow Zn + CO$	$FeO + C \rightarrow Fe + CO$

Fig. 7. The main reactions taking place in the Waelz process [1]

3. MODEL PROFITABILITY ANALYSIS

The analysis of the profitability of zinc recovery processes from waste was carried out on the basis of a model prepared by ZGH „Bolesław" S.A., which is based on indicators determined on the basis of the average consumption of materials in a period of 12 months, reflecting the actual size of metallurgical waste processing. It was developed for the processing of 100,000 tons of waste. The analysis included the costs of:

- purchase of production materials:
  - dusts,
  - reducer,
  - limestone,
  - quartz sand,
  - $Ca(OH)_2$,
- gas,
- energy,
- compressed air,
- external services (waste management, equipment services, transport),
- taxes and fees (CO_2 emission fee, environmental fees, taxes and other fees),
- materials for repairs and repair services (conditions in which furnaces operate expose them to frequent repairs),
- remuneration for employees,
- health and safety services,
- depreciation of assets.

Table 4 summarizes the data on the percentage of zinc in zinc-bearing waste and the amount of zinc oxide produced from dusts and sludge, along with the percentage of zinc in the resulting product.

Table 5 shows the demand for materials necessary to carry out the waste recycling process, calculated on the basis of 100,000 tons.

Table 5 shows that the consumption of energy carriers for the processing of zinc-bearing dusts is higher than in the case of zinc-bearing sludges. This discrepancy is visible primarily in the demand for energy and limestone.

Table 6 shows the amount of slag generated in the recycling process, which is one of the by-products of the overburdening process.

Table 6 shows that for the adopted model, the processing of steelmaking dust generates over 4.5 times more slag than the processing of zinc-bearing sludge. With regard to the assumed model, Table 4 presents data on the percentage share of dusts and sludges purchased for the needs of the process. Taking into account the percentage share of materials in the overall waste processing, along with their origin (own resources, purchase from external companies, processing services), the revenue from the recovery process was calculated (Table 7).

The total revenue from the processing of zinc-bearing waste in the model under consideration consists primarily of the profit from the recovery of zinc from dusts, however, in order to ensure the continuity of the process and achieve the highest possible profitability, it is necessary to purchase them (an additional portion), which is a significant financial burden for the plant.

Table 4
Balance of the processing of dusts and zinc-bearing materials [16]

Type	Wet weight [t]	H_2O [%]	Dry weight [t]	Zn [%]	Zn content [t]
Dust (processing)	70,420.3	2.44	68,702.0	26.21	18,006.8
Sludges (processing)	29,579.7	31.04	20,398.2	16.28	3,320.8
Production ZnO from dusts*	27,493.0	0.00	27,493.0	61.42	16,886.2
Production ZnO from sludges**	7,736.0	8.40	7,086.2	44.05	3,121.5

* dusts yeld: 93.78%; **sludges yeld: 94.00%

Table 5
Consumption of materials, gas, compressed air and energy in the process of processing zinc-bearing dusts and sludges per 100,000 tons of waste [16]

Type	Material			Gas [m^3]	Compressed air [m^3]	Energy [kWh]
	reducer [t]	limestone [t]	*quartz sand [t]			
Zinc-bearing dusts	22,568.7	6,842.7	0	830,576.1	10,104,908.2	4,368,693.5
Zinc-bearing sludges	9,043.5	2,323.4	807.1	779,472.0	7,525,320.5	1,421,217.3
Total	31,612.2	9,166.1	807.1	1,610,048.1	17,630,228.7	5,789,910.8

Table 6
The amount of slag produced during the processing of zinc-bearing dusts and sludges [16]

Slag from dust processing [t]	58,070.3
Slag from sludge processing [t]	12,690.5
Total [t]	70,760.8

Table 7
Revenue from the zinc recovery process per 100,000 tons of waste [16]

Source of income	Amount [PLN]
Dust processing service	5,700,000
Sludge processing service	240,000
Dust purchase cost	4,800,000
Total	1,140,000

4. SUMMARY

With reference to the above-presented results of modeling the profitability of zinc recovery from waste in the sintering process, the following conclusions can be formulated:

- a significant cost that contributes to the final profitability of the overburdening process is the purchase of an additional amount of zinc-bearing dust. The adopted analysis, based on the adopted indicators, assumed the need to purchase 40% of dust to ensure the profitability of recycling.
- in addition to the fixed costs of the process of zinc recovery from waste, which includes, among others, purchase of materials, depreciation of assets, costs of energy, utilities, staff costs, ongoing repairs, the total profitability is also affected by:
  - zinc prices on the London Metal Exchange (LME),
  - exchange rates,
  - external services, e.g. waste management,
  - taxes and fees, i.e. CO_2 emissions fee, environmental fees.
- from the economic point of view, the most favorable factor for profitability is an increase in the price of zinc on the London Metal Exchange and an increase in the dollar exchange rate, with the lowest possible price of materials necessary for processing from waste suppliers,
- alternative sources of input materials with the highest possible zinc content should be sought.

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