Environment and structural change in zinc production

by Per Storm

In the present study, some technological and economic fundamentals of zinc production are discussed. An economic assessment is made where possible production from zinc containing electric arc furnace dust is compared to conventional production from ore. The assessment shows that it is reasonable to assume that zinc production from dust would be profitable under present market conditions. This would, however, still require some technological problems to be solved.

Dr.-Ing. Per Storm, Department of Industrial Economics and Management, Royal Institute of Technology (KTH),
S-100 44 Stockholm, Sweden.
e-mail: Per_Storm@lector.kth.se

Man has used zinc as a working surface for a long time. In continental Europe, zinc is common as roofing and as counters in bars.[1] The usefulness of zinc in such applications is mainly due to its non-corrosive nature and the relative ease with which it attaches to steel surfaces. That has also lead to the rise of zinc coating (galvanising) as the most common application of zinc today.

Although zinc coating initially began already in the 1830:s, a secular phase of rapid growth in the output of coated steel took place in the 1980:s; see figure 1. As a result of this, an increased amount of zinc coated scrap will appear on the scrap market in coming years. When zinc coated scrap is melted, zinc will evaporate alongside with other volatile substances and will subsequently precipitate as a dust from the furnaces offgases in the gas cleaning equipment. Each tonne of scrap-based steel, entails the formation of more than 10 kilos of dust. Each year, roughly 400 ktonnes of zinc containing dust is generated in western Europe and 300 ktonnes in Japan[2].

As the dust represents a potential environmental hazard due to its leachability[3], an increased environmental awareness has led to a growing demand to take care of contaminated dust. It is desirable, and often necessary, to reduce the content of heavy metals in the dust and form a vitrified, non-leachable slag. This has led to an increased interest in zinc production from electric arc furnace (EAF) dust containing zinc[4]. For several reasons this cannot be done through conventional zinc producing methods. Electric arc furnace dust usually contains a large amount of iron, either as iron oxides or as zinc ferrite ($ZnO{\cdot}Fe_2O_3$). Zinc ferrite is insoluble in relatively dilute acid (used in conventional zinc production). In addition, traditional leaching techniques are neither designed to treat raw materials with such high iron and low zinc content, nor designed to cope with the amounts of leach residue produced due to the small metal content in the feed. The final drawback is the halide content, i.e. the fluoride and chloride normally found in EAF dust and which will concentrate in, and severely disturb, the final zinc deposition. Accordingly, various techniques to produce zinc directly from EAF dust have been proposed. When - or if - these processes become commercial this will clearly influence the structure and economics of the zinc industry.

This paper will discuss part of the current technological development in the field of zinc production based on EAF dust. Here, I will try to show how environmental issues have influenced technological solutions and highlight some possible economic consequences thereof. I will also touch upon policy questions which may - or may not - influence the present development.

The point of view of this paper is a pragmatic one (using a technological perspective). Accordingly, no simple cause-and-effect explanations to the complex interaction between technology, economy and society will be offered (such as, e.g., that this is simply a question of "technology management" or "vertical integration"). Instead, a more vivid description of the technological development will be given. This description assumes that several intentions are inherent in the development and, thus, that it could not be attributed to (or driven by) a single body.

This kind of discussions often contains "environmental economics" or environmental policy design. However, the focus is on tecnological development and it´s possible effects on production and industry structure rather than how to effect the development or the structural changes. Discussion and theoretical treatment on the formation of environmental fees and taxes is both vivid and extensive but will - as has been noted above- not be treated within the scope of this investigation.

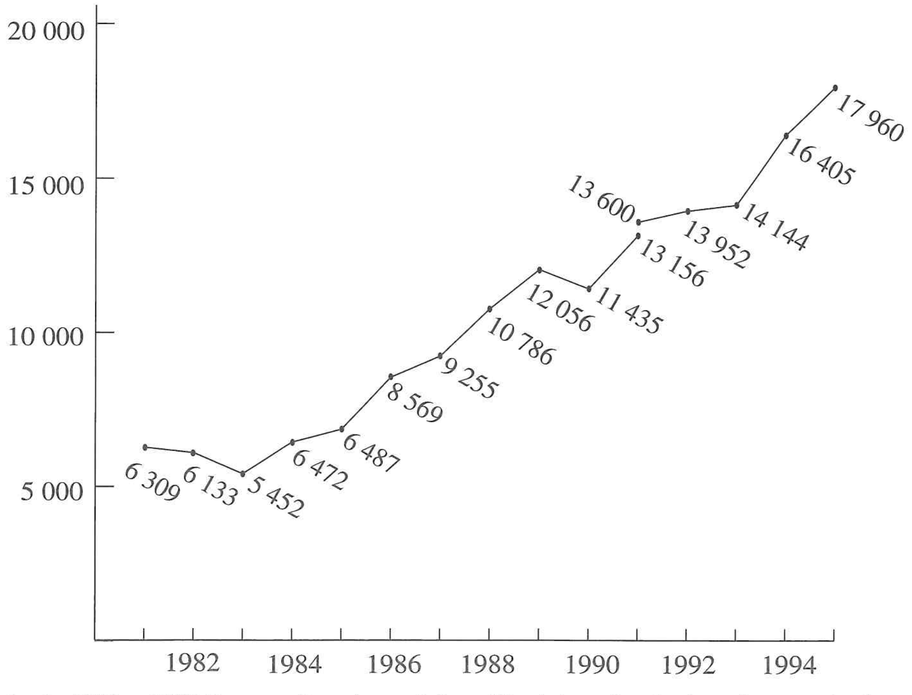
Technological development addressing ecological questions

Recently, there has been an increased pressure from governmental authorities, legislation etc. to take care of dusts, other wastes and by-products. In the United States, the Environmental Protection Agency (EPA) has stated that EAF dust containing more then 15 per cent zinc must be re-processed using thermal reduction methods. Dust with less zinc content may be disposed of as landfill provided that it is chemically stable[5]. Dust from an EAF is considered to be a hazardous waste. As a result, a different kind of measure has been taken. On the one hand, intense development has been focused on the possibility of pacifying the dust to avoid leakage of any harmful substance. On the other hand, there is the possibility of using the dust as a raw material in zinc production, i.e. converting the waste into a valuable resource. The second of these possible developments is, as indicated, in focus for this paper.

The inquiry as to what structural consequences the present development may have must be carried out in two steps. First, it is necessary to introduce zinc production and *how* the technology has developed in response to environmental issues. Secondly, possible technologically influenced industrial changes can be idintified. Accordingly, we will start by discussing how conventional zinc production is carried out and how the alternative new methods are designed.

Zinc is generally mined as zinc blende (ZnS) and upgraded to a concentrate at the mine. The concentrate is then shipped to a zinc plant where it is roasted (converted to zinc oxide) and treated either hydrometallurgically or pyrometallurgically. Approximately 80 per cent of zinc slabs were hydrometallurgically produced[6].

Figure 1. Production of zinc coated sheet and strip, inEuropean Union, 15 countries (t)

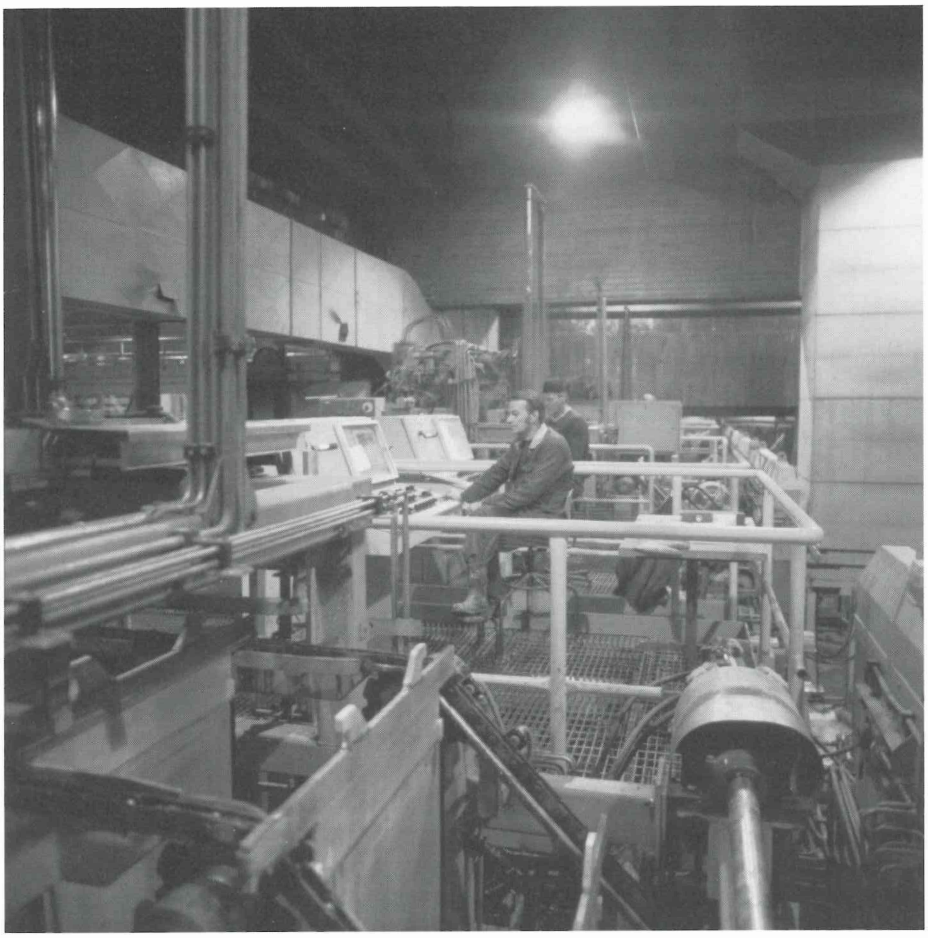


Note: In 1991 – 1992 the reporting changed from ”tinplate, galvanised products, and other coated products” to ”tinplate, other metal coated products, and organic coated products”.
Source: IISI.

The hydrometallurgical treatment is carried out according to one of three major processes: the Jarosite process, the Götite process and the Haematite process. Which one is used depends on the content of valuable by-product metals besides zinc in the concentrate. The Jarosite process is the most common but has environmental disadvantages compared to the other two, due to a large and non-disposable residue. The processes consist of three general steps: a dissolution of zinc (and, unfortunately, some impurities); a purification step where pure zinc metal powder and substances to remove impurities are added to the solution so that valuable metals (cementation of copper, silver and gold) and impurities precipitate; electrolysis, where the contained zinc is deposited on large cathodes. The cathode zinc may then be remelted and alloyed but no further purification is necessary.

EAF dust often contains zinc ferrite, a compound insoluble in the mild acid solutions used in the above mentioned processes. Due its amphoteric nature, it is - in principle - possible to dissolve zinc oxide in both acid and alkaline solutions. Hence, several basic leaching methods have been proposed to take care of EAF dust such as the Cebedeau process and the Caron zinc process[7]. The latter, the Caron zinc process, comprises four main steps: a roasting of ferrite containing materials under reducing conditions; secondly, the non-ferrous metal calcine is dissolved (and purified); the iron containing leach residue is recovered and finally non-ferrous metals are recovered through cementation, solvent extraction or electrowinning. This process has some environmental advantages over conventional leaching, such as an absence of toxic constituents in the residue, and reportedly a lower capital and operating cost. At present, the process is untested except in laboratory scale, and its development is still in its infancy. The other alternative leaching processes, the Cebedeau process[8], has been running as a pilot

Electrolysis, Outokumpu Zinc Oy in Kokkola, Finland.



plant but has not yet reach commercialisation. The process is based on leaching of EAF dust with sodium oxide. Dust containing zinc and lead (and copper in minute amounts) is dissolved in the basic solution but iron compounds stay insoluble and are obtained as a residue to the leaching. Lead and copper in the solution may be cemented with zinc powder. High purity zinc powder may be obtained by electrolyses. However, the zinc powder obtained in the process, does not meet the demand of a special high grade product and must be refluxed to meet such standards. This process also has the environmental advantage over conventional leaching by avioding the use of acid solutions, as well as obtaining a harmless residue (iron oxides).

In the main pyrometallurgical process, the Imperial Smelting Process (ISP), the roasted concentrate is sintered and added to a shaft furnace in which the zinc oxide is reduced to zinc metal vapour[9] (approximately 1000 °C). The zinc vapour follows other furnace gases to a condenser. In the "splash condenser", liquid lead (at 450 °C) acts as a solution agent for the zinc and when the temperature is further lowered, zinc will start to precipitate. Zinc exiting from the condenser will contain lead and to obtain purer zinc it has to be upgraded through refluxing. There lead and zinc are separated by boiling point differentiation.

Through the years, raw materials of different compositions and origin have been used in pyrometallurgical zinc production. Accordingly, different process solutions have been put forward to enhance the usefulness of different materials. For example, in order to upgrade zinc ores, which were not leachable or treatable according to the IS-process due to high content of iron, a rotary furnace process known as the Waeltz process was started in Germany already in 1923.[10] This process lay-out has lately been used as a method to upgrade zinc containing EAF dust in an environmentally sound way. The Waeltz process is described in detail in a large number of publications so only a brief outline will be given here.

In the Wealtz process, EAF dust is fed into a rotary furnace with coal dust. Incoming lead, zinc and cadmium will be reduced in the furnace and evaporated with volatile salts. Heavier elements in the charge, such as iron, will form a slag. As the metal containing gas is cooled, the metals will re-oxidise and precipitate as a dust in the gas cleaning equipment. This *secondary* dust may then be pelletized and charged into an Imperial smelting furnace (see above). Reports have been published indicating the possibility to operate Imperial smelting furnaces with 100 per cent briquette zinc oxide as feed.[11]

One of the main issues in the environmental debate is the use of energy (as it is often produced from fossil fuels or nuclear plants). As pyrometallurgical processes - smelting of zinc included - are very energy intensive, this has brought forward development that tries to increase energy efficiency in such processes. One way of doing this, is to apply high energy density plasma generators in metallurgical processes. One of the few commercially successful applications is the Plasmadust process. It stems from a line of plasma based reduction processes developed by SKF Steel Engineering (presently ScanArc Plasma Technologies). Plasmadust was developed as an alternative to the ISP - initially named plasmazinc - but the process was found to function equally well for dust feed. Thus, it was further developed to treat waste products from steel production such as stainless dust and commercial steel furnace. Apart from feeding oxidic waste material, it is

Table 1. Relative operating costs (roughly 1990)

	VM	ISP	Wealtz -ISP	Plasma-dust	Slag reducer	Cebe-deau
Zinc conc/dust[1]	66	65	–	–	–	–
Net feed material[2]	-7	6	37	37	12	2
Energy[3]	17	8	9	36	12	25
Labour & overhead	24	23	53	36	36	90
Operating cost	100	102	99	109	60	117

Notes: 1. Dust value is set to 0 USD/t. 2. Feed material, including reactants such as coal and coke, minus credits. 3. Electrical energy and auxiliary fuel.

also possible to inject fine ground zinc ore or calcine into the furnace. In the process, energy for heating the reactants and for the reactions are supplied by plasma generators in the lower part of a reduction shaft furnace.

In 1984, an enterprise to upgrade steel furnace dust was started in Landskrona (Sweden). It operates as a separate company, ScanDust AB, and initially treated both stainless and carbon steel dust in separate campaigns. In the ScanDust operation, the plasmadust process has been in continuous operation since the start. The carbon steel dust treatment was closed down in 1987 and the process is currently operating on 100 per cent stainless dust. However, during the years 1984 to 1987, more than 200 tonnes of prime western grade zinc were produced.

Recently, based on the experience of developing the plasma based processes, ScanArc Plasma Technologies has developed a complementary process called Slag Reduction.[12] In Slag Reduction, a molten slag bath is created by melting oxidic raw materials or feeding molten slag into the furnace. The energy consumption of the process may be lowered further by premelting the feed which can subsequently be fed into the furnace. Underneath the slag surface plasma generators are supplying the required energy to maintain liquid phase and for required reactions. By feeding a controlled amount of reducing agent (carbon or hydro carbon), a selective reduction of various metals can be obtained. Due to the intense mixing in the plasma jet, it is possible to operate the reducer very close to equilibrium. A reduction of the zinc and lead content of an EAF dust to below one tenth of a per cent without reducing any of the iron oxide was reported. Compared to the plasmadust process, the slag reduction process is more suited to treat materials with low metal content and it consumes less energy than the plasmadust process. So far, the largest problem with pyrometallurgically based processes has been the condensing of zinc exiting the furnace. Several alternative concepts to the Imperial Smelting condensor have been put forward but none of them are yet successful.

Table 2. Relative production cost for zinc (roughly 1990)

Process route	VM	ISP	Wealtz-ISP	Plasma-dust	Slag reducer	Cebe-deau
Operating cost	100	102	99	109	60	117
Cost of capital	96	96	74	94	64	40
Production cost	196	198	173	203	124	157

Besides the mentioned processes, several others have been proposed. They are, however, to be regarded as variations on the same themes presented here, i.e., recirculating the zinc to create a secondary dust or trying to smelt the dust directly using high energy (plasma) methods.

Economic problems and possibilities

In the previous paragraph, the technological development was highlighted. This is, however, only one of the components necessary for the requisitioning of a new raw material. Another component is, of course, the economics of the chosen conversion route and the organisation of the production chain.[13] This raises two questions: are the proposed conversion routes profitable? and, how does the institutional structure of the production chain influence the possibility of using EAF dust as a base for zinc production?

To tentatively answer these questions, an assessment of the cost structure of the mentioned zinc conversion routes was carried out. The selection of studied processes is arbitrary but, hopefully, representative. In the assessment, costs for input material such as concentrates, dust, and reagents and energy[14] were relatively well specified and minor costs, such as labour, supervising and maintenance were attributed in a stereotypical way which is common in this type of assessment[15]. The assessment of operating cost for zinc conversion (i.e. capital charges excluded) resulted in a relative cost advantage for the conventional hydrometallurgical conversion (see table below), mainly due to the possibility of crediting valuable by-products such as copper, silver and gold.[16]

It is also clear from the table that if the slag reducers process would be as efficient in commercial operation as has

Roasting plant, Outokumpu Zinc Oy in Kokkola, Finland.

been shown in test trial it may very well be a formidable competitor to the existing processes. This assessment may questioned from several points-of-view. Its implications should therefor not be overestimated, price changes on different substances may, e.g., heavily influence the results. There is also the question of the capital charge.

Besides being energy intensive, metallurgical production is also capital intensive. Accordingly, the cost of capital is an essential figure in this type of assessment. It is also one of the most difficult figures to assess, inter alia, due to differences in the way capital charges are attributed to the products, differences in context (company, organisation) and differences in exchange rates over time. Notwithstanding these difficulties, a rough production cost was estimated (see table 2).[17]

Although the estimate is not flawless, other investigations have come to similar results. The production (or supply cost) was reported to be between 25 ¢/lb and 39 ¢/lb (in 1989 USD)[18] for conventional production indicating that the estimation above (roughly 45 to 55 ¢/lb depending on capital charge) was rather conservative. It also implies that the production cost for EAF dust based production using best available technology would approximately be 35 ¢/lb - still a competitive figure.

With zinc prices hovering around 50 ¢/lb it is highly unlikely that the production cost calculated above would motivate an investment in *conventional* zinc production - or in zinc production from dust in order to compete with conventional production. However, from a dust producers perspective, the situation tends to be somewhat different. If the dust output is so large that the environmental cost is equivalent to an annual cost for a zinc investment, competitive dust treatment could be a possible alternative. Today, such cost relationships are obviously not at hand. On the contrary, in an article on the Wealtz-process, the economics are treated in the following manor:

"The described treatment route [the Wealtz route] for EAF dust should not be considered as a way to recover zinc and lead. On the contrary, it offers a feasible means of avoiding the necessity of dumping a waste material which is not suited for recycling in the steel industry and, at the same time, the recovery of valuable metals gives a contribution to the expenses. We see the described way as an example for ´waste management´ combined with the ´recycling philosophy´. Although the necessary treatment charge which has to be paid from the steel works in Europe are in order of 30-50 USD/t of dust depending of the local situation, this is already cheaper than dumping in special sites and, last but not least, more pregnant from the point of view of protection of the environment."[19]

However, this leads us to the second of the two questions above: are there other relationships, e.g. organisational structures or the relationships between different steps in zinc production chain, that might influence the establishment of a dust based zinc venture?

Pricing in the production chain

Price and price formation heavily influence the use of a metal. How prices are formed is strongly dependant of the ownership and control of the different actors in the process. To clarify the influence of the organisational structure, let's begin by looking at price formation in the zinc production chain.

Fundamentally, zinc metal prices are either formed as market determined prices or producer determined prices. Trading of zinc metal takes place on the big commodity exchanges such as the London Metal Exchange (LME) or the Commodity Exchange in New York (COMEX). There, market determined prices can be said to be set on three things: (*i*) the output on the market (from producers and stockholders); (*ii*) the actual demand for the commodity, and (*iii*) the buyers expectations of the near future output. Such prices are highly sensitive and adjust almost instantaneously to changes in supply and demand conditions.

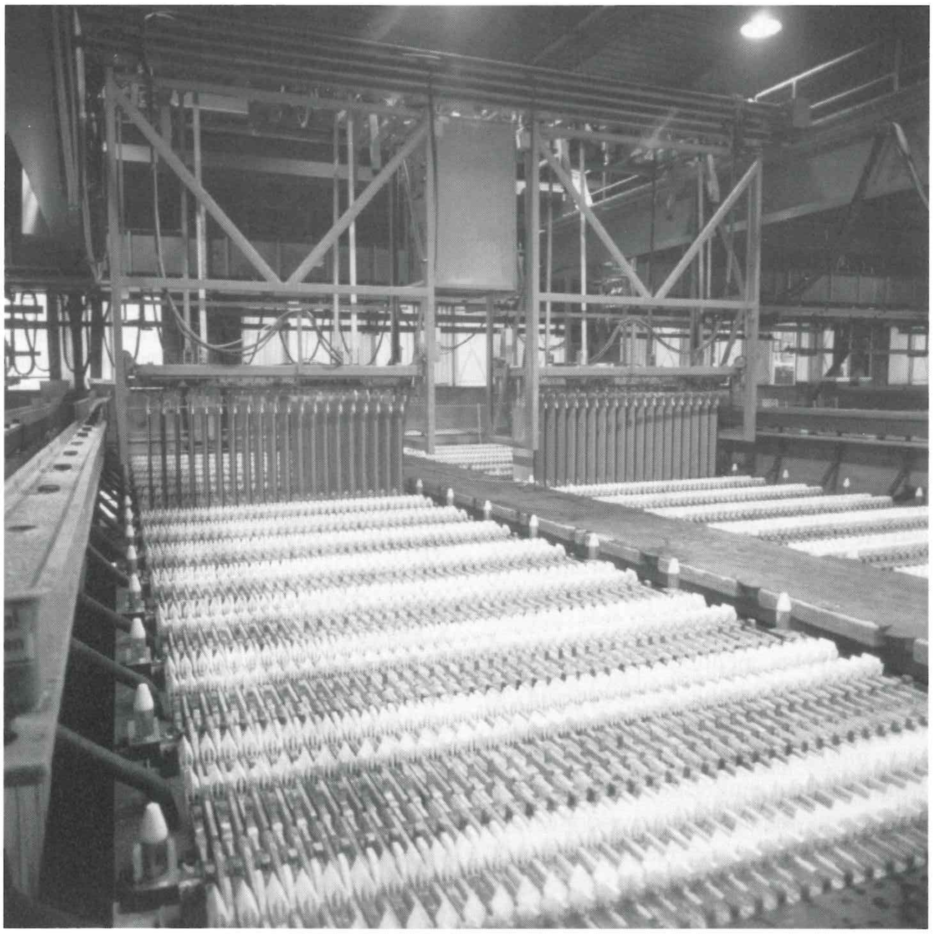
On the other hand, producer determined prices are set in negotiations between the different actors on the market. It is noteworthy that the part of the zinc traded at e.g. the LME is only a minor part of concluded zinc contracts. The dominating part of the commodity trade on the commodity exchanges are paper transactions without any physical content. Most of the physical trade is carried out elsewhere.

Different prices are also quoted on the grounds of different qualities. Zinc is quoted either as Prime Western Grade (PWG, also known as Good Ordinary Brand, GOB, or grade IV) containing 98.5 per cent zinc; High Grade (HG) of 99.95 per cent zinc; and Special High Grade zinc (SHG, or grade I) containing 99.99 per cent zinc. There has been a tendency to shift from lower to higher grades in some main applications. However, in some special applications, low quality zinc may be used as successfully as higher grades.

Table 3. Current processors of EAF dust (1990)

Country/Company	Location	Start-up	Process	Product kt	Dust cap. kt	Zinc cap.
France						
Recytec	Fouquières	1993	Wealtz	ZnO (crude)	85	16
Germany						
BUS	Duisburg	n.a.	Wealtz	ZnO (crude)	58	14
	Freiberg	n.a.	Wealtz	ZnO (crude)	45	10
Italy						
Nuova Samin	Ponte Nossa	n.a.	Wealtz	ZnO (crude)	65	10
Japan						
Himiji Steel	Himeij	1975	Wealtz	ZnO (crude)	35	Japan produces approximately 40 kt zinc from EAF dust.
Kaneko Trading	Sekijo	1987	Wealtz	ZnO (crude)	60	
Mitsui Mining	Miike	n.a.	Half Shaft	ZnO (crude)	60	
Toho Zinc	Onahama	1973	Electric	ZnO (com.)^2	50	
Soetsu Metal	Aizu	1974	Wealtz	ZnO (crude)	60	
Sumitomo Metal	Shisaka	n.a.	Wealtz	ZnO (crude)	60	
Spain						
Aser	Bilbao	1987	Wealtz	ZnO (crude)	85	16
USA						
Florida Steel	Jackson, TN	1989	Plasma	Zn (metal)	7.2	1.4
HRD	Palmerton, PA	1981	Wealtz	ZnO (crude)	245	n.a.
	Calumet, IL	1988	Wealtz	ZnO (crude)	72	75
	Rockwood, TN	1990	Wealtz	ZnO (crude)	90	n.a.
	Monaca, PA	1990	Flame	ZnO	18	n.a.
North Star Steel	Beaumont, TX	1992	Flame	ZnO	30	5
Nucor-Yamato	Blythewille, AR	1989	Plasma	Zn (metal)	11	1.8
Zia Technology	Caldwell, TX	1990	Rotary	Zn (metal)	27	4.5

Notes: n.a. = not available or not specified. 1. Commercial grade.
Source: ILZSG.



Zinc electrolysis stripping machine, Outokumpu Zinc Oy in Kokkola, Finland.

The most frequently used zinc price, and the base price in zinc containing contracts, was traditionally the European producer price (grace IV). In the last years the price base has changed to a LME special high grade quotation both in Europe and in the United States. About 75 per cent of zinc concentrates in the western world are priced using the LME special high grade price as a reference.[20]

Feed material such as zinc concentrates are priced according to a different method. Zinc is sold from the mine to the smelter as a concentrate and from the smelter to the market as a metal (and then from the market to the consumer of the metal). In between sales, the smelter is awarded a fee known as treatment charge. The treatment charge should cover the cost (including profit) for the smelter to convert the concentrate to zinc. The price negotiation between the mine and the smelter is based on a reference price for zinc metal on the market, i.e. a SHG quotation on LME at a certain time (e.g., the first fortnight of October of the preceding year). The reference price is, in some way, depicting the price of zinc to the consumer at the time. In the negotiation between the miner and the smelter, the treatment charge will be expressed in an absolute and a relative value. The absolute value will be the figure as negotiated. The relative value is called "percentage of payable zinc content", i.e., the percentage of zinc in the concentrate times the percentage of payable zinc content. In fact, this will be the splitting down of the return per tonne of concentrate between mines and smelters. Average treatment charges used to be roughly 40 per cent . To give an example: If the price notation is 850 USD/tonne zinc, the zinc content in the concentrate is 50 per cent and the relative treatment charge is 35 per cent , this will make an absolute (or negotiated) figure of ($850 \times 0.50 \times 0.35$ =) 149 USD.

This pricing principle might lead to a squeezing of the smelter between the mine and the market (i.e. the exchange) [21]. Whether or not this is the case depends on the ownership and control of the smelter. If the smelter is an in-house smelter in an integrated company (mine to exchange), the problem will be one of internal trading. If the smelter is a free operator, the problem will be one of commercial negotiations. A few years ago, slightly less then half of the world mine production was not connected to any in-house smelter.

Environmentally induced structural change

As indicated above, increased environmental demands have spawned technological research of different kinds. Zinc output from EAF dust does not affect the market in more than marginal ways today - and will not do so in the near future - this will most likely change in a longer time-perspective. (A summary of active dust processors is found in table 3).

What may happen to the zinc industry structure? Again, assuming that technological questions are managed, we will see an increased number of facilities which convert dust to a high grade raw material (e.g. zinc oxide ready to leach). This may bring about a change in the bargaining power structure of the zinc production chain. Smelters will gain bargaining power and change their negotiating position relative to the mine.[22] From having a clear ore-dependency they might be able to achieve the same kind of double (or multiple) sourcing of raw materials which is common in many other industries (of which the automotive industry is probably the most well known example)·[23]

There are, of course, other ways of explaining possible structural changes, such as the transaction cost approach. However, this would be outside the scope of the present discussion which has, as noted previously, a technological perspective.

The consequences for a zinc production chain might be several. Let us summarise the arguments so far. In conventional economic thinking, the marginal unit on a market operates at the market price (i.e. at zero profit). In case of increased supply - and a subsequent price decrease - this unit will be crowded out. However, if the object under study is *not* a perfect market (which in this case could be the LME) but the entire production chain as a whole, what is the marginal unit is no longer obvious. In case a competing production chain is established independent of financial incentives, as when steelworks pay dust converters to convert zinc dust independent of LME zinc prices (dependant on regulations or market demands on another market, here the steel market) this might lead to a crowding out of the entire production chain from mine to market. Accordingly, this might shift what is perceived as the "marginal unit" and mining capacity will be crowded out. This could indicate a form of reversed action based on enviromental demands. Even if the zinc price falls due to over supply of the market the regulator will not be mine output but the treatment fee that the steelworks pay the dust converters.

A development like the one indicated above could also change the way EAF dust is perceived. In a rather distant future, zinc containing EAF dust might be seen as a low zinc, high iron calcine rather than as a waste material.

The above mentioned development will have policy implications and may in part also depend on political action. Further increased environmental demands from different authorities will undoubtedly favour the depicted development. A too rapid increase in environmental regulations might, however, lead to sub-optimal solutions where second rate technology, in locations with low or no environmental demands, prevail.[24] Accordingly, the on-going technological development is not only a technological affair.

Notes

1. In Sweden, the more exclusive metal copper was used as roofing material on official buildings. This is mainly due to the existence of the Falu Coppermine which produced high grade copper ore for the Swedish Crown from the turn of the last millennia to the turn of the present. The Falu mine is also the origin of the worlds oldest still operative share holder company, STORA.

2. Western Europe i.e. the European part of the OECD, except Ireland, Portugal, Greece and Turkey. The output of dust was calculated as an average of 12 kg dust per tonne steel produced; see Kola (1990 p. 455) and for Japan, see Tsuneyama et al. (1990 p. 467).

3. From local concentration of zinc containing waste, the metal may be dissolved in the ground water and, hence, occur in plants, animals and aquatic organism in toxic concentrations. Studies have shown that concentrations as low as 10 -15 mg/l of Zn^{2+} may effect aquatic organism and concentrations around 100 mg/l of Zn^{2+} may be toxic in plants. In ordinary fresh water the concentration is between 1 -10 mg/l of Zn^{2+}; see e.g. Naturvårdverket (1993 & 1988).

4. Contrary to what is sometimes believed, there is no inherent trade-off between ecology and economy. There exist - as will also be shown here - clear possibilities to combine the two, for an elaboration see e.g. Porter and van der Linde (1995).

5. Wu & Themelis (1992 p. 35).

6. Yamada et al. (1985 pp. 62).

7. A more extensive description of the Cebedeau process is given in Frenay et al. (1986 p. 417) and the Caron process in Nyirenda (1990 p. 319) and van Put et al (1989 p. 641).

8. Frenay et. al. (1986 p. 419).

9. Zinc oxide cannot be reduced by carbon under 1000 °C (although is melts at 419 °C). Since the boiling point of zinc metal is 908°C, the metal must be collected as a vapour and condensed so that it is not again oxidised.

10. Unger (1986 p. 413).

11. See Kola (1990) and Hopkin & Richards (1970).

12. Both the description of the plasmadust process and the slag reducer refers to Santén (1992 p. 211) and (1993, pp. 1, 6).

13. The twin concepts conversion route and production chain are simply devided in the following way: a zinc *conversion route* refers to the sequence of unit processes from zinc ore to zinc metal, whereas the *production chain* focuses on the institutional structure, i.e. companies, involved in the same transformation.

14. Several studies have pointed out that hydrometallurgical processes are as energy consuming as pyrometallurgical, see e.g. Hopkin & Richards (1978 p. 16); Kellogg (1980 p. 42) or Davey (1990 p. 52).

15. The calculations were mainly based on the following sources: Vieille Montagne, Kellogg (1980); ISP Kellogg (1980, 1990); Wealtz-ISP, Thomas & Clifton (1987), Kola (1990); Plasmadust, Slag reducer, Santén (1993); Cebedeau, Frenay et al. (1986). Where consumption figures, etc., clearly were outdated they have been updated by the author (through interviews, etc.) and recalculated to fit the current case. In the assessment, average productivity figures was assumed to be somewhat higher for pyrometallurgical processes than for hydrometallurgical: 41 ton zinc per man-month compared to 37.7 (Yamada 1985 p. 81). This assumption was also reinforced by the figures presented by Williams (1990 p. 447) and Davey (1990). The latter reported a productivity of 100 ktonnes per year from 250 employed.

16. Several by-products will occur at different stages of zinc production. In assessing production cost (or the cost of supply), these are mainly credited, i.e. added as a negative cost in the cost assessment. Slightly less than 10 per cent of the world zinc output is so called "fatal production" - the production cost less credits are below zero (given a reasonably common ways of distributing costs). Exactly how the different by-products should be credited is dependant on the perspective of the investigation. In published assessments, different forms of crediting have been carried out. In the calculations which were the basis for this paper, by-products are only credited with a sum equal to the cost of recovering them, e.g., lead-silver residues from the hydrometallurgical process, (74 g Ag/tonne concentrate) is credited according to the reclamation cost, 3 USD/oz; see Rodier 1990.

17. The cost of a 100 ktonnes hydrometallurgical plant was reported to approximately 300 MUSD (in total); see Goto et al. (1988 p. 319)

and Wickham (1990 p. 20), for an ISP smelter the building cost was reported to roughly 2000 USD/tonne; see Nurse (1992 p. 72). The investment in the Wealtz furnace was recalculated from Thomas & Clifton, (1987), for the plasmadust and slag reducer processes the investment was appreciated from figures provided by ScanArc Plasma Technologies in Solbrand & Östlund (1991), and for the Cebedeau process, from figures presented by Fernay, also in Solbrand & Östlund (1991).

18. Davey (1990 p. 41).

19. Kola (1990 p. 462).

20. See Millbank (1988 p. 13) and Goeckmann (1989 p. 49) for the European scene and Lovatt (1991 p. 45) for the American.

21. An elaboration of this and the pricing feature is given in Bué (1987 p. 70) and Gardner (1995 p. 36)

22. Both March (1966) and Pfeffer & Salancik (1978) discuss the concept of power and inter-company relationships more in detail. These kinds of negotiating games are also highlighted in Odhnoff & Laxén-Payró (1985).

23. See mainly Womack, Jones and Roos(1990). A study with more technological focus in the same industry is Blomgren (1997).

24. For an elaboration, see Porter and van der Linde (1995 p. 124).

References

Blomgren H. (1997), *Arbetsfördelningen i produktionskedjan*, Dr. Diss, Dept. Industrial Economics & Management, KTH, Stockholm (in Swedish).

Bué C. (1987), "Challanges for European Smelter", *Metal Bulletin Monthly*, August, pp 67–74.

Davey T.R.A. (1990), "Towards AD 2000"; *Lead-Zinc´90, Proc. World Symp. Metallurgy and Environmental Control*; TMS-AIME, Anaheim; pp 39–54.

Frenay J., Hissel J., Ferlay S. (1986), "Zinc and lead recovery from EAF dust by caustic soda process" *Proc. 44, the Elec. Furnace Conf.*, Dallas, pp 417–421.

Gardner A (1995), Concs trade gears up for annual talks, *Metal Bulletin Monthly*, Octobe, pp 36–39.

Goeckmann K. (1989), "Zinc on the LME - a miners view", *Metal Bulletin Monthly*, june, pp 47-49.

Goto S., Nishikawa M., Fujikawa M. (1989), "Semi-pilot Plant Test for Injection Smelting of Zinc Calcine", *Proc. Int´l Symp. Metallurgical Processes of the Year 2000 and Beyond*,TMS, Las Vegas, pp 301–321.

Hopkins W., Richards A.W. (1978), "Energy Conservation in the Zinc-Lead Blast Furnace", *J. Metals* November, pp 12–17.

Kellogg H.H. (1980), "Energy Use in Zinc Extraction", *Lead-Zinc-Tin ’80, Proc. World Symp. Metallurgy and Environmental Control*, TMS-AIME, Las Vegas.

Kellogg H.H. (1990), "A Practical Model of the Imperial Smelting Zinc-Lead Blast Furnace", *Lead-Zinc´90, Proc. World Symposium of Metallurgy and Environmental Control*, TMS-AIME, Anaheim, pp 549–569.

Kola R. (1990), "The Processing of Steelworks Waste" *Lead-Zinc´90, Proc. World Symp. Metallurgy and Environmental Control*, TMS-AIME, Anaheim, pp 453–464.

Lovatt M. (1991), "US Consumers Lament Zinc Price Switch", *Metal Bulletin Monthly*, June, pp 45.

March J. (1966), The Power of Power, in Easton D (ed.), *Varieties fo Political Theory*, Prentice-Hall, New York.

Millbank P. (1988), "Zinc concentrates head for a surplus", *Metal Bulletin Monthly*, November, pp 10–13.

Naturvårdverket (1988), *Zink i miljön*, Report no 3429 (in Swedish).

Naturvårdverket (1993), *Metallerna och miljön, Miljön i Sverige - tillsånd och trender (MIST)*, Report no 4135 (in Swedish).

Nurse M. (1994), "Zinc recovery takes off", *Metal Bulletin Monthly*, July, pp 57–60.

Nyirenda R.L. (1990), "An appraisal of the Caron Zinc Process when Zinc Ferrite is Reduced to a Magnetite Containing Product", *Minerals Engineering*, Vol 3, No 3/4 , pp 319–329.

Odhnoff J., Laxén-Payró M. (1985), *The Internationalization of Enterprises. Three Cases of Foreign Investment Decisions*, The Swedish Institue for Working Life, Stockholm.

Pfeffer J. & Salancik G. (1978), *The external control of organizations. A resource dendence perspective*, Harper & Row, New York (etc.).

Porter M. & van der Linde C. (1995), Green and Competetive, Ending the Stalemate, *Harvard Business Review*, September–October, pp 120–134.

von Put J.W., de Bruijn W., Duyvesteyn W.P.C. (1988), "The Caron Zinc Process", *Proc. Fine Particles´88*, CIMM, Montreal, pp 641 ff.

Rodier D.D. (1990), An overview of Silver and Trace Metal Recovery Strategies in the Zinc Industry", *Lead-Zinc´90, Proc. World Symp. Metallurgy and Environmental Control*, TMS-AIME, Anaheim, pp 57– 85.

Santén S. (1992), "Metallurgical Processes Based upon Plasma Technology", *Proc. John Olof Edström Symp.*, pp 208–211.

Santén S. (1993), "Recovery of Metals from Steelmaking Dusts*", Proc. McMaster Univ. Iron & Steelmaking symp. "Pretreatment and Reclamation of Dusts, Sludges and Scales in Steel Plants",* Hamilton.

Solbrand K., Östlund C. (1991), "*Omhändertagande av zinkrikt stoft från ljusbågsugn*", M.Sc. Thesis, Dep. Production Technology, mining and steel industry.

Thomas S.S., Clifton E.D. (1987), "Economic Evaluation of the HTR Process for Treating EAF Dust", *Proc. 45, th Elec. Furnace Conf.*, Dallas, pp 413–419.

Tsuneyyama, N., Takewaki M., Yasukawa M. (1990), "Production of Zinc Oxide for Zinc Smelting Process from EAF Dust at Shisaka Works", *Lead-Zinc´90, Proc. World Symp. Metallurgy and Environmental Control*, TMS-AIME, Anaheim, pp 465–476.

Unger T.W. (1986), "Waelz kiln recovery process for electric arc furnace dust" *Proc. 44, th Elec. Furnace Conf.*, Dallas, pp 413–415

Wickham G.A. (1990), "Zinc Industry in the 1990, s", *Lead-Zinc´90, Proc. World Symp. Metallurgy and Environmental Control*, TMS-AIME, Anaheim, pp 13–21.

Williams R.L. (1990), "The Monaca Electrothermic Smelter - the Old Becomes New", *Lead-Zinc´90, Proc. World Symp. Metallurgy and Environmental Control*, TMS-AIME, Anaheim, pp 439–449.

Womack J., Jones D., Roos D. (1990), *The machine that changed the world*, Rawson Ass. et al., New York etc.

Wu L., Themelis N.J. (1992), " The Flach Reduction of Electric Arc Furnace Dusts", *J. Metals, January*, pp 35–39.

Yamada F., Terayama T., Enomota S. (1985), "A Survey of Operating Situation of Zinc Smelters and Refineries on the World", *Zinc’85, Proc. Int´l Symp. Extractive Metallurgy of Zinc*, Tokyo, pp 61–92. ■