The Use of LCA for the Environmental Evaluation of the Recycling of Galvanised Steel

Christina Viklund-WHITE

MEFOS, Box 812, SE-971 25 LULEÅ, Sweden. E-mail: cvw@mefos.se

(Received on July 1, 1999; accepted in final form on November 17, 1999)

Life Cycle Assessment has been used to compare the environmental performance of landfilling of the zinc used for galvanising steel with recycling by a number processes. Hypothetical process routes were composed involving three different EAF dust treatment processes, Waelz kiln, DC-furnace, and EZINEX, as well as scrap dezincing. The study shows that recycling of zinc used for galvanising steel clearly has environmental benefits in that it saves zinc resources. However, zinc recovery does not necessarily decrease the potential impact on global warming and acidification. The magnitude of these two impact categories is tightly correlated with the amount and type of primary energy consumed in a process. Due to the high electricity consumption in the dezincing process, this route has the highest impact on Global Warming Potential as well as Acidification Potential. The major part of the energy requirement for the production of zinc from primary and secondary sources is consumed in the reduction of ZnO to Zn. The consequence is that the theoretically possible saving in primary energy by recycling zinc-containing materials is relatively small. The impact categories land use and waste generation are not considered in this study, but most likely the evaluation of such impacts would further increase the potential environmental impact of the landfill alternative. The results also show that the location of an electricity-intensive process highly affects the potential environmental impact. Comparing process and material alternatives in LCA studies where branch average data is used is therefore considerably more complex than when LCA is used within a company.

KEY WORDS: LCA; zinc; galvanised steel; recycling; environmental; EAF dust; dezincing.

1. Introduction

The optimisation of a process or a process route has traditionally only included economic and technological factors. However, it is to an increasing extent realised that this approach is insufficient and that a third determinant, environmental factors, also have to be considered. The need for a tool to systematically evaluate environmental issues in a production system has led to the development of Life Cycle Assessment.

1.1. Life Cycle Assessment

In an LCA-study material and energy flows as well as emissions are identified and quantified across the entire life cycle of a product, process, or system. Interpretation of the acquired data gives guidance in decisions that are made within a company or in society. Life Cycle Assessment is carried out in four coupled steps according to Fig. 1. In the initial step the goal and scope should be clearly defined. The intended application of the study is stated and the system is described, in writing as well as graphically in the form of a flow schematic. During the inventory analysis step data is collected and relevant inputs and outputs to the system, including resources, emissions, and use of water and land are calculated.

The third phase, the impact assessment, intends to evaluate the significance of potential environmental impacts based on the data from the inventory analysis. The impact assessment phase of an LCA based on ISO 14040 consists of mandatory elements, selection of impact categories, classification, and characterisation, as well as the optional weighting. A number of models exist for evaluating impact categories and the choice depends on the goal and scope of the study. In the optional weighting step the category indicator results are weighed against each other and for this several methods based upon various principles have been developed.

The findings from the inventory analysis and the impact assessment lay the basis for the interpretation, which further provides information for conclusions and recommendations. As apparent from Fig. 1, conducting an LCA is an iterative process, and thus the scope may be modified as the

Fig. 1. Phases of an LCA.
study is carried out.

1.2. Zinc in Steelmaking

Currently around 3 million tonnes of zinc is used for galvanising steel yearly, amounting to 48% of the total world zinc consumption.1) The growth rate of the use of zinc for galvanising has over the last 20 years been 3.4% per year and it is predicted that this rate will increase in the near future. Although a substantial portion of the world zinc consumption is used in galvanising operations only 6% of the zinc produced from secondary sources originate from steelmaking dusts. It is clear that substantial zinc values present in steelmaking dusts are excluded from the cycle by being landfilled. LCA can be used as a tool to environmentally evaluate different options to recover zinc used for galvanising steel.

Due to its relatively low boiling point, zinc present in steelmaking furnaces will almost completely end up in the off-gas. The off-gas is treated using wet or dry gas-treatment equipment generating sludges and dusts amounting to 10 to 20 kg per ton of steel and containing the condensed zinc in the form of zinc oxide and zinc ferrite. The concentration of zinc in the dust will depend on the amount of galvanised scrap that is charged to the steelmaking furnace. Dust from electric arc furnaces producing carbon steel contains in general 15 to 35% zinc.

Figure 2 represents a schematic of the life cycle of zinc in steelmaking. A number of options can be identified in the system. The zinc used for galvanising steel can be recovered, either from the dust or by dezincing the scrap prior to its remelting. The dezincing step can be performed through vaporisation or hydrometallurgically. For the extraction of zinc from EAF dust a number of commercial processes, hydrometallurgical as well as pyrometallurgical, are available. The motive for the large interest in finding suitable treatment methods for EAF dust is, in addition to the economic potential from the recovery of its zinc content, the fact that the dust may be classified as being hazardous. The classification of dust as a hazardous waste together with increasing scarcity of available land, provide for that landfilling costs are escalating.

Most processes utilised for the recovery of zinc from primary raw materials can in principle be applied for the treatment of steelmaking dusts. However, an upgrading step is usually required to yield a material of higher zinc content and to remove harmful impurities such as halogens.

Alternatively, steelmaking dusts of higher zinc content can be processed directly in the ISP process by the mixing with primary zinc raw materials and secondary material of higher zinc content and purity.2)

Dust formed in the steelmaking processes can also be recirculated back to the furnace to increase the zinc concentration, and thus the economical value of the dust. The whole quantity of dust can be recirculated until a certain zinc concentration has been reached or, alternatively, only a fraction having a low zinc content is recirculated and a bleed is constantly withdrawn from the process. Recirculating only the low zinc fraction will limit the impact on furnace performance as well as the increase in energy consumption while still upgrading the zinc content of the dust that is being shipped for treatment. The environmental effects of internal recirculation of EAF dust have been studied elsewhere.3)

2. Goal and Scope

The aim of the project is to evaluate the use of LCA within the metallurgical industry in general and for the management of waste- and by-products from this industry in particular. For this, the assessment of the recycling of zinc coated scrap was considered as a suitable case study. The scope of this particular study is to evaluate the environmental benefits of recovering the zinc used for galvanising steel.

2.1. System Definition

This study evaluates the recycling of zinc coated scrap to an EAF. A number of hypothetical options that can be identified in the system are compared. Figure 3 displays the process routes investigated and the system conditions used are presented in Table 1. An EAF is used for the production of steel of which 28% is coated with 12.7 kg zinc per ton of steel. Following the user-phase galvanised as well as uncoated steel is scrapped and recycled back to the furnace. The galvanised steel can optionally go through a dezincing process in which the zinc is removed. Dezincing the scrap provides for that the dust generated contains low concentrations of zinc. The dust can be landfilled without any significant zinc values leaving the system. If the zinc coating is not stripped from the scrap the dust will contain essentially all the zinc and the dust can be treated by three different processes to extract the zinc. An additional option, where
2.2. Primary Zinc Production

The production of zinc other than that from EAF dust is assumed to be carried out in Western Europe. Although secondary zinc sources account for nearly 40% of the total zinc production in this area, in this study the zinc is assumed to originate from primary ore. Mining of ore and concentration take place in North America as well as in Northern Europe. Of the primary zinc produced in Europe 85% is made by the hydrometallurgical route and the remaining 15% through the pyrometallurgical Imperial Smelting Process. The data used represents a weighed average between these two processes as well as a weighed average between the zinc-producing countries.

2.3. Dezincing

In the dezincing process the galvanised scrap is shredded and brought into contact with hot caustic soda whereby the zinc is dissolved. Zinc is then recovered from the solution by electrolysis. Since the galvanised scrap is assumed to be shredded whether it goes through dezincing or not, the energy consumption for the shredder is not included.

2.4. Dust Treatment

Zinc is commercially extracted from EAF dust by the use of a number of different processes. These are based on either pyrometallurgical or hydrometallurgical principles. In pyrometallurgical processes the zinc is vapourised and recovered as zinc oxide or metallic zinc. The most commonly used practice for treating EAF dust is by the use of a Waelz kiln. Through the application of hydrometallurgical methods the zinc is leached in either acidic or caustic solutions and recovered from the solution electrolytically.

The dust treatment processes considered in this study are Waelz kiln, EZINEX and DC-furnace. These processes were selected as they are quite different in character. Processes that are employed for treating EAF dust are also commonly used for processing other secondary zinc sources and a mix of various materials can thus be treated. In this study however, it is assumed that EAF dust is the only zinc feed-stock treated in the processes.

2.4.1. Waelz Kiln Process

The Waelz kiln is the most commonly employed treatment method for EAF dust in the world, processing approximately 1 million tons per year.5) The Waelz kiln was originally developed as an upgrading process for lean zinc ores and zinc bearing by-products and consists of a rotating kiln, typically 50 to 60 long with a shell diameter of 3.6 to 4.2 m. The EAF dust is fed into the slightly inclined kiln in the form of green pellets mixed coke breeze and/or anthracite and return coke. The Waelz process can be operated with a basic or an acidic slag. The slag basicity (CaO+MgO)/SiO2) is kept below 0.5 or above 2 and is adjusted by the addition of limestone or silica. The zinc contained in the dust is, together with lead and cadmium, reduced by the reducing agent in the reduction zone of the kiln having a temperature of 1 100 to 1 200°C. The zinc fumes are combusted in the freeboard with air entering the front end of the kiln and the oxide is cooled and collected in a baghouse or electrostatic precipitator. The slag can be utilised as a construction material.

The Waelz-oxide has a zinc content of 55 to 60% and is leached for the removal of chloride and fluoride. In this study, it is assumed that zinc is produced from the washed Waelz oxide by electrolysis although the Imperial Smelting Process can also be employed. The Waelz process is assumed to be located in Denmark adjacent to the steel plant and the generated Waelz oxide is sent to the electrolytic zinc plant in Norway.

2.4.2. EZINEX Process

The EZINEX process is developed by Engitec Impianti S.p.A in Italy. Currently there is only one plant in commercial operation but several contracts are under negotiation.

| Table 1. Process options studied. |
|-----------------------------------|
| **Steelmaking** | EAF in Denmark |
| **Scrap** | 28% galvanised scrap with 12.69 kg Zn per ton steel |
| **Process options** | a. Waelz kiln - electrolysis |
| | b. Waelz kiln - electrolysis |
| | c. DC-furnace - electrolysis |
| | d. Landfilling recirculation |
| **Primary zinc** | Weighed average between hydro- and pyrometallurgical production of zinc in Europe (85%-13%) |

Fig. 3. Definition of system.
The process recovers metallic zinc from EAF dust through a hydrometallurgical system. The steelmaking dust is mixed with recirculated spent electrolyte based on ammonium and alkali chloride at a temperature of 70–80°C for 1 hr. The main reaction is:

\[ \text{ZnO} + 2\text{NH}_4\text{Cl} \rightarrow \text{Zn(NH}_3\text{)}_2\text{Cl}_2 + \text{H}_2\text{O} \]

Zinc-ferrite is not dissolved and the solubilisation degree of zinc is thus dependent amount of ferrite present in the dust, which can be estimated based on the prevalent Zn/Fe ratio. A ratio of 1 : 1 means that approximately 55 % of the zinc is dissolved. The slurry consisting mainly of iron oxides and zinc ferrite is filtered in a filter press and the cake is dried to a moisture-content below 10 %. The oxide residue is mixed with 20 % coal (dry basis) and granulated before being recycled to the EAF.

The leachate is purified from heavy metals contamination through cementation with zinc powder. The cement consists mainly of lead (70 %) and is sold to lead–zinc smelters. In the electrolysis cell the zinc is deposited on the titanium cathodes while the graphite anodes release nitrogen. The process produces metallic zinc ingots of high purity level that can be used in galvanising operations. The zinc-depleted solution is purged through an evaporator that separates salts by concentration and crystallisation. The solution is then recirculated to the leaching phase.

2.4.3. DC-furnace Route

The DC-furnace route for the treatment of EAF dust consists of three separate steps; zinc reduction, soda leaching, and electrolysis. The process is not yet commercialised and has only been tested in pilot scale. The process was chosen for this study since it has been subject for investigations for development in Scandinavia. The process concept is also different from the other two EAF dust treatment processes selected. In the first step, the production of a zinc-rich clinker, the process utilises a DC-furnace with a conductive bottom that acts as the cathode and a hollow graphite electrode functioning as the anode. A molten metal bath promotes uniform temperature and sufficient electrical contact. EAF dust together with coke is fed through the hollow electrode providing for direct exposure to the hot plasma. The zinc is reduced and volatilised together with lead and is further combusted by air in a combustion chamber. A mixed oxide consisting of zinc, lead and halogen is generated. Prior to zinc recovery, which is performed by the electrolytic process, it is necessary that the halogens be removed. This is performed by leaching in soda.

To display how the environmental performance of a process option is dependent on the energy-mix used for the production of electricity calculations are carried out for two different locations for the DC-furnace, Denmark and Norway. In Norway the electricity is almost entirely generated from hydropower, while in Denmark fossil fuels are mainly used. The calcine generated is however treated at the zinc plant in Norway in both cases.

3. Inventory

3.1. Data Quality

Data for primary zinc production is obtained from a study conducted for the International Zinc Association-Europe (IZA study). This collection of data represents the period 1994–95 of majority of Western European zinc producers, producing together 75 % of total European production. For the dezincing process the data used is acquired from a commercial plant. For two of the dust treatment processes considered in this study, the EZINEX process and the DC-furnace route, the data used is obtained from the operation of pilot plants. Industrial data is used for the Waelz kiln process.

Inventory data for the production and combustion of energy as well as transport data are aggregated data from ETH-Zürich which is included in the DEAM database of the LCA software TEAM. Data for additives are also taken out of the DEAM database and their origin are BUWAL 250 and ETH.

3.2. Primary Zinc Production

The zinc ore used contains 6 % Zn and is beneficiated to generate a concentrate with 56.6 % Zn. All of the zinc producers participating in the IZA study buy zinc concentrates on the open market and thus shipping distances corresponding to delivery to Belgium/Netherlands was assumed. The weighed average for shipping of 1 kg of concentrate to Belgium/Netherlands is 10.45 ton-km sea transport and 0.11 ton-km of rail transport. The zinc is then produced by electrolysis or in the Imperial Smelting Process. Table 2 shows the main material energy inputs for the production of zinc ingots from ore. Allocation to elements of value in the ore (lead, cadmium, silver and sulphur) has been performed.

3.3. Dezincing of Scrap

The materials and energy consumption resulting from dezincing of scrap is presented in Table 3. In the calculations 90 % recovery efficiency of zinc is assumed.

3.4. Waelz Kiln–Electrolysis Route

Data for the Waelz process are obtained from sources from Berzelius Umwelt-Service AG and includes materials consumption, by-product generation as well as emissions from a production facility. The zinc bearing feed is assumed to be 100 % EAF dust and the kiln operates with acidic slag. The slag product contains 0.3 % Zn. Data for the electrolysis step are based on the data from an electrolysis process produced hydro- and pyrometallurgically produced zinc according to European production.

Table 2. Energy demand and main raw materials for the production of one ton of zinc (weighed average between hydro- and pyrometallurgically produced zinc according to European production).

| Stream               | Unit | Amount |
|----------------------|------|--------|
| Energy               |      |        |
| Electricity          | MJ   | 13900  |
| Oil                  | MJ   | 2160   |
| Coal and gas         | MJ   | 364    |
| Input                |      |        |
| Zinc (in ore)        | kg   | 1050   |
| Limestone            | kg   | 69     |
| Bauxite              | kg   | 25     |
| Sulphur              | kg   | 25     |
| NaCl                 | kg   | 9.1    |
| Output               |      |        |
| Zinc                 | kg   | 1000   |
| Waste rock           | kg   | 5500   |
| Jarosite residue     | kg   | 560    |

Table 3.
sis plant using primary raw materials. The zinc yield in the reduction and the soda leaching steps combined is assumed to be 95%, and in the electrolysis 97%. The materials and energy balance for the three step combined is summarised in Table 4.

### 3.5. EZINEX Process

Data for the EZINEX process is acquired from various sources provided by Engitec. The materials and energy balance is shown in Table 5. No allocation between the products is done. The ferrite residue, which is the largest product from the process, is not an output from the system since it is returned to the EAF. The process utilises DC current for the electrolytic recovery of zinc and the demand is assumed to be directly proportional to the zinc concentration of the dust. The AC current demand is however assumed to be proportional to the dust amount.

### 3.6. DC-Furnace–Electrolysis Route

The origin of the inventory data for the DC-furnace step are various publications from pilot-plant trials conducted at MEFOS. These publications are not official. The mass and energy balances for all three steps included in the DC-furnace route have been aggregated and are shown in Table 6. The zinc yield in the reduction and the soda leaching steps combined is assumed to be 95%, and in the electrolysis 97%. Since the data used for the DC-furnace and the soda leaching steps is not obtained from a production plant, detailed information regarding emissions are not available. Estimated emission data for the DC-furnace has been included in the calculations. Data for the electrolysis step are based on the data from an electrolysis plant using primary raw materials.

### 4. Impact Assessment

Comparison of the environmental impacts of the various system options are performed on the basis of primary energy demand together with the impact categories Global Warming Potential (GWP), Acidification Potential (AP) and consumption of zinc. Global Warming Potential and Acidification Potential are normally the most dominant when studying energy-intensive systems while consumption of zinc resources was included since saving natural resources is an important aspect of recycling. It would have been of interest to also take into account the emissions of heavy metals. However, it has not been possible to obtain data on this from all processes. The results are presented as normalised data with the landfill alternative as a reference. Normalisation is here carried out by subtracting the reference value from the results of the other alternatives. The contribution from each process step expressed as a percentage of the total impact is also displayed.

#### 4.1. Primary Energy

Figure 4 shows that the primary energy consumption in the dezincing process route is considerably higher than in the other alternatives. Figure 5 reveals that the major part of the energy is consumed in the actual dezincing step.
where all energy added is in the form of electricity. It can be noted that the electricity required for the electrolysis of zinc in this process greatly exceeds that of other electrolysis processes studied here. This is further accentuated in Table 7 where the electricity demand for the production of 1 kg of zinc by electrolysis in the various processes are displayed. Of the total primary energy consumption for the production of primary zinc around 17% can be ascribed to the steps preceding the electrolysis, i.e. mining, concentration, and transportation. The high energy consumption of the Waelz process step is mainly attributed to the coke consumption. The only process alternative consuming less primary energy than the landfill alternative is the DC-electrolysis route when the DC-furnace is located in Norway. The consumption in the EZINEX process and the Danish DC-alternative is somewhat higher.

4.2. Global Warming Potential

From Fig. 6 it is clear that also the Global Warming Potential is highest for the dezincing route. Since the dezincing operation is assumed to be located in Denmark where the electricity is about 95% fossil fuel based, the generation of CO₂ is very high. The significant decrease in Global Warming Potential when the DC-furnace is placed in Norway instead of in Denmark is apparent from Fig. 6. As Fig. 7 illustrates, the contribution to the Global Warming Potential from the secondary zinc electrolysis, which is performed in Norway, is small. Again, the only alternative exhibiting lower potential impact than the landfill option is when a DC-furnace placed in Norway is used for upgrading the dust.

4.3. Acidification Potential

As Fig. 8 shows, the dezincing option displays the highest potential impact also for the category Acidification Potential. Again, the effect of fossil fuel based electricity production is manifested by the two DC-furnace alternatives. The data obtained for the Waelz process reported no emissions of SO₂, despite the significant consumption of coke in the process. It is likely that the process emits a certain amount of SO₂ and that the relatively low Acidification Potential of the Waelz process alternative as illustrated in Fig. 8 does not depict the reality. Figure 9 illustrates the relative contributions from the various process steps.

Table 7. Electricity consumption for the production of 1 kg of zinc.

| Process          | Source Description  | Electricity Consumption |
|------------------|----------------------|-------------------------|
| Electrolysis of calcine | Calcine with 60% Zn | 13 MJ                   |
| EZINEX           | Dust with 35% Zn     | 19 MJ                   |
| Dezincing of scrap | Scrap with 1.3% Zn   | 54 MJ                   |

Fig. 4. Primary energy demand of process options studied normalised to landfill alternative.

Fig. 5. Contribution of process steps as a percentage of total demand of primary energy.

Fig. 6. Global warming potential of process options studied normalised to landfill alternative.
4.4. Consumption of Zinc as Ore

The consumption of zinc as ore normalised to the landfill alternative is presented in Fig. 10. Naturally, all process routes exhibit less depletion of zinc reserves than when the zinc disappears from the technosphere by being landfilled.

5. Discussion and Conclusions

The results indicate that the recycling of zinc used for galvanising steel does not necessarily decrease the potential impact on the global warming and the acidification. The magnitude of these two impact categories is tightly connected to the energy consumption in a process. During the production of primary zinc a contribution to the acidification potential is also made by the process emissions of SO$_2$. This amount is however minor compared to the SO$_2$-emissions caused by producing the energy consumed in the processes. The major part of the energy for the production of primary zinc is consumed in the reduction of ZnO to Zn, which is done pyro-, or hydrometallurgically. The difference in gross energy for producing zinc from ore by the two processes is small, less than 4% as calculated in the IZA study. The reduction of the oxide to zinc is required also when the zinc is produced from secondary sources. The consequence is that the theoretically possible savings in primary energy is relatively small and in reality, it appears as the reduction in the primary processes are more efficient and energy consumption is thus smaller. In the treatment options based on the DC-furnace and the Waelz kiln the reduction of ZnO to Zn is done twice, first high-temperature reduction with coke followed by electrolysis. It should be remembered that heat can potentially be recovered in these processes, a fact that has not been considered in this study, and the total energy consumption in these process routes would thus be reduced.

The minimal effect on Global Warming Potential when Norwegian electricity is used in electricity-intensive processes is well known. This is also evidenced in this study. However, also hydropower plants cause environmental impacts, e.g. by putting large land areas under water and altering the conditions for aquatic organisms. The quantification of these impacts is more complex.

Obviously the consumption of zinc as ore is higher in the landfill alternative than when zinc is recovered, either from the dust or from the scrap. The generation of waste together with emissions of metals to air and to water are impacts that are not considered in this study. The data on metals emissions from the various processes are not complete and calculations would thus not give correct results. The generation of wastes in the processes depends to a large extent on if slags can be converted into useful aggregates. Zinc-containing dust is however regarded as a waste and metals may potentially leach from the landfill. Also, mining activities generate large amounts of waste, in the mine as well as in the mill. Another source of waste is the generation of jarosite residue from the electrolysis of zinc. The amount is approximately proportional to the Fe-content of the feedstock and is on average 0.56 kg per kg zinc produced from ore. The Fe- to Zn-ratio in the Waelz-oxide and particularly in the DC-furnace calcine is considerably lower and thus the generation of jarosite residue is lower than in primary production. This can be observed by comparing the calculated values given in Tables 2, 4 and 6. These are points that further increase the potential environmental impact of the landfill alternative but that would require more detailed data for quantification.

This investigation shows how LCA could be applied within a company for providing information that together with technical and economical aspects can be used for deci-
The significant influence that the energy-mix used for electricity generation has on the environmental performance of energy-intensive processes is clear. Thus the potential impact is largely dependent on the location of the operations and the origin of the raw materials. Comparing process and material alternatives in LCA studies where branch average data is used is therefore considerably more intricate than when LCA is used within a company. The access to detailed and precise data provides that LCA can be used as a tool in evaluating process and material choices as well as identifying environmentally weak points in the system.

Acknowledgement

The author is grateful to the Minerals and Metals Recycling Research Centre, Mimer, located at Luleå University of Technology, which provided the funds for conducting this research.

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