

An environmental assessment of lead and zinc production processes

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ABSTRACT

A study was carried out to compare the environmental impacts of a number of process routes for lead and zinc metal production from sulphide ores using Life Cycle Assessment methodology and based on average industry data derived from the literature. The processes investigated were:

- Blast furnace production of lead
- Imperial Smelting Process for lead and zinc production
- Electrowinning of zinc

with the mining and mineral processing stages common to all three routes.

The effect of a number of process variables, namely ore grade, fuel source for electricity generation and efficiency of generation, on the environmental impacts was also examined. The environmental impact categories considered in the study were:

- Total (or full cycle) energy consumption
- Global Warming Potential (GWP)
- Acidification Potential (AP)

The results of the study show that when produced separately, zinc production is more than twice as energy intensive as lead production (viz. 48 and 20 MJ/kg respectively), however when produced jointly by the Imperial Smelting process, the energy intensity of the two metals is not all that dissimilar (viz. 36 and 32 MJ/kg respectively). The metal production and refining stage was found to make the greatest contribution to the overall environmental impacts for all three processes. The study also highlighted the importance of taking a life cycle approach when comparing the environmental impacts of different processes.

INTRODUCTION

The now widely accepted concept of sustainable development has focussed attention on the supply chains and life cycles in which minerals and energy resource processing take part. In the overall supply chain of material needs, resource processing represents a particularly critical stage for the potential release of gaseous, liquid and solid emissions to the environment. It is here that chemical transformations often take place to extract metals, generate power and produce industrial minerals. A number of tools and methodologies have been developed in recent years to assess the potential environmental impacts associated with a product, process or activity during its entire life cycle. Life Cycle Assessment (LCA) is one such tool and is sometimes referred to as “cradle-to-

grave” analysis. A brief description of LCA methodology is given in a previous paper (Norgate and Rankin, 2000) and a more detailed description is given by Weidema (1997). CSIRO Minerals has been using LCA to examine the main metal production processes practised in Australia with a view to assisting in the development of processes that minimise the environmental impacts of metal production. This paper describes one such study on lead and zinc production.

Geologically, lead and zinc minerals frequently occur together and, traditionally, lead and zinc have been considered as a single industry. Global production of lead and zinc in 1999 has been estimated at 6.2 Mt and 8 Mt respectively (Hassall and Roberts, 2000), worth approximately US\$3 b and US\$8 b respectively. Ore grades in Australia typically range from 6 - 12% Zn and 3 - 6% Pb, with a production tonnage-weighted average of 8.6% Zn and 5.5% Pb. Both individual metal concentrates and bulk concentrate (>10% each of lead and zinc, with 45 – 60% total metal) are produced from these ores. The economic benefits of producing separate flotation concentrates in place of a bulk concentrate are well established in practice. For many mine operators the bulk concentrate is regarded as the last resort, the repository of metals for which the separation has become too expensive or which is not physically possible with current technology. The main processing routes for lead and zinc metal production are shown in Figure 1 with the relative proportions of metal produced globally by each process being approximately as follows:

- Lead - Blast Furnace process 80%
- Imperial Smelting process 10%
- Zinc - Electrolytic process 90%
- Imperial Smelting process 8%

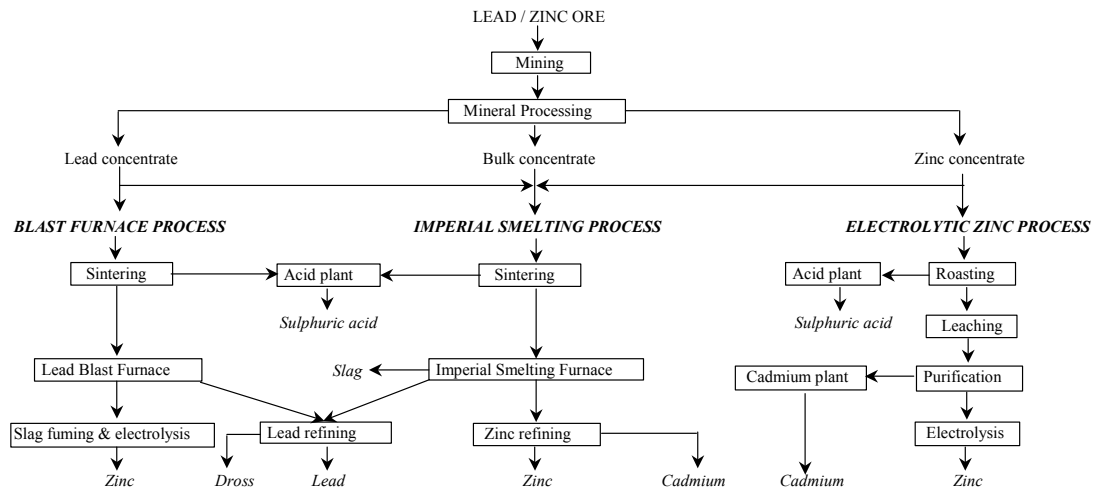


Figure 1. Main processing routes for lead and zinc production.

A number of other processing routes, eg. Kivcet and QSL, account for the remainder of the lead production. The three processing routes for lead and zinc production shown in Figure 1 were the subject of the LCA described in this paper.

SCOPE OF LCA

The system boundary for the LCA was restricted to “cradle-to-gate”; i.e., the metal production processes were considered only up to the point where refined metallic products are made available to the secondary manufacturing sector. This limited form of LCA is quite valid for comparing the environmental impacts of the “process” stage of the life cycle, assuming that the “product” stage of the life cycle of a metal is the same irrespective of how it was produced.

The three processing routes outlined above were considered in the study, with all routes including a mining (underground) stage and a mineral beneficiation stage. All processes also included an acid plant to capture SO₂ emissions. However in the case of the Blast furnace process, the slag fuming and electrolysis stage shown in Figure 1 was specifically excluded from the system boundary. Generic flowsheets of each process were drawn up and used to establish individual LCA spreadsheet models. The flowsheets were constructed at a level of detail consistent with publicly available data for each process. Thus the Electrolytic zinc process flowsheet model consisted of three process steps (mining, mineral processing and roasting/leaching/electrolysis combined) while the Imperial Smelting process flowsheet model consisted of six process steps (mining, mineral processing, sintering, smelting, lead refining and zinc refining). The data used for input to each model were derived solely from the literature, with the data being cross-checked with more than one source where possible. These data and their sources are summarised in Table 1, although for the sake of brevity those inputs not relevant to the impact categories considered have been omitted from the table. Some inventory values in this table are the mean of several reported literature values and in this case not all references are shown, only those for typical values.

The environmental impact categories considered in the study were greenhouse and acid rain gas emissions, both on an individual and aggregated basis (ie. Global Warming Potential (GWP) and Acidification Potential (AP) for greenhouse and acid rain gas emissions respectively). Total solid and liquid wastes were also included, as was total (or full cycle) energy consumption. The functional unit used in the study was 1 kg of refined metal, ie. all impacts were expressed per kg of refined lead or zinc.

ASSUMPTIONS

The following assumptions were made in carrying out the LCA study:

- the mine and concentrator are in close proximity, as are the smelter and refinery and hence transport of materials between these respective facilities can be ignored,

- the concentrates are transported a nominal distance of 1000 km (by ship) from the concentrator to the smelter,
- diesel fuel for mining equipment is transported by road (diesel) a nominal distance of 500 km to the mine,
- coal and coke is transported by road (diesel) a nominal distance of 500 km to the smelter,
- electrical power is generated using black coal as the fuel source,
- the power plant efficiency is 35%,
- recovery of SO₂ in the acid plant is 98%,
- all ancillary materials are either generated on site (e.g., oxygen) or are available nearby (e.g., limestone, silica) and hence transport of these materials can be ignored,

Table 1. Inventory data used in study

Stage	Process		Inventory			Reference
Mining			Diesel fuel	0.002	t/t ore	Molinia (1993), Westcott & Hall (1993) Molinia (1993) Leahy (1993) Leahy (1993)
			Electricity	13	kWh/t ore	
			Mine drainage	0.78	t/t ore	
			Waste rock	0.18	t/t ore	
Mineral Processing			Electricity	31	kWh/t ore	Various sources Watters (1993) Pasminco (2000)
			Grinding media	0.001	t/t ore	
			Water	0.95	t/t ore	
Metal Production	Lead Blast Furnace	<i>Sintering</i>	Limestone	0.237	t/t conc	Ramus & Clift (1993) Yamada et al (1985) Moriya (1989), Kellogg (1980) Siegmund (2000), Moriya (1989) Siegmund (2000) Siegmund (2000) Siegmund (2000) Moriya (1989), Gunji et al (1994) Moor (2000) Moriya (1989)
			Natural gas	0.004	t/t conc	
			Electricity	335 ¹	kWh/t conc	
		<i>BF</i>	Coke	0.092	t/t sinter	
			Limestone	0.126	t/t sinter	
			Silica	0.057	t/t sinter	
			Oxygen	0.027	t/t sinter	
	<i>Refining</i>	Electricity	95	kWh/t sinter		
		Natural gas	0.030	t/t Pb		
		Electricity	3	kWh/t Pb		
	Imperial Smelting Furnace	<i>Sintering</i>	Limestone	0.237	t/t conc	Ramus & Clift (1993) Yamada et al (1985) Moriya (1989), Kellogg (1980) Tsuyuguchi et al (1993) Siegmund (2000), Kellogg (1980) Siegmund (2000) Siegmund (2000) Yamada (1985) Moor (2000) Moriya (1989) Hopkin (1980) Kellogg (1980) Kellogg (1980)
			Natural gas	0.004	t/t conc	
			Electricity	335 ¹	kWh/t conc	
<i>ISF</i>		Coke	0.833	t/t Zn		
		Limestone	0.177	t/t Zn		
		Silica	0.027	t/t Zn		
		Oxygen	0	t/t Zn		
<i>Lead refining</i>		Electricity	455	kWh/t Zn		
		Natural gas	0.030	t/t Pb		
<i>Zinc refining</i>	Electricity	3	kWh/t Pb			
	Natural gas	0.109	t/t Zn			
	Electricity	25	kWh/t Zn			
Electrolytic Zinc	<i>Leaching</i>	Natural gas	0.028	t/t Zn		
	<i>Electrolysis</i>	Electricity	4000 ²	kWh/t Zn		
		Lime	0.016	t/t Zn		
		Oxygen	0.090	t/t Zn		
		Water	12.3	t/t Zn		

1. Includes 270 kWh/t conc for acid plant

2. Includes 3200 kWh/t Zn for Electrolysis, 800 kWh/t Zn for other plant (including roasting, leaching, acid plant)

- ore grade is 8.6% Zn, 5.5% Pb, 20.0% S,
- concentrator recovery is 73.8% Pb to lead concentrate, 79.5% Zn to zinc concentrate, 81.4% Pb and 84.4% Zn to bulk concentrate,
- lead concentrate grade is 57.9% Pb, 6.1% Zn and 18.8% S,
- zinc concentrate grade is 50.3% Zn, 3.1% Pb and 29.8% S,
- bulk concentrate grade is 35.3% Zn, 21.6% Pb and 26.1% S,
- Imperial Smelting process recovery is 95% Zn and 95% Pb,
- Blast Furnace process recovery is 98.3% Pb,
- Electrolytic zinc process recovery is 98.5% Zn,
- the metal products from the different processes for each metal type have essentially the same quality, however it is recognised in the case of zinc that there are minor differences in grade (typically 0.1 –2%) from the two processes and that they are not directly substitutable.

CO-PRODUCT ALLOCATION

While lead and zinc are traditionally mined together as pointed out above, the concentrates produced from these mixed ores are often processed separately to produce refined lead metal (the lead blast furnace process) and refined zinc metal (the electrolytic zinc process). However both lead and zinc are produced in the Imperial Smelting process. In fact the ability of the Imperial Smelting process to treat materials containing both lead and zinc is its main advantage, and it consumes virtually all of the world's production of bulk concentrates. The remainder of the concentrates fed to the Imperial Smelting process tend to be materials that are less acceptable to electrolytic zinc plants or lead smelters. This co-production of lead and zinc in the Imperial Smelting process raises the issue of co-product allocation.

Many industrial processes produce multiple useful outputs called co-products. For such processes, the environmental impacts associated with the process must be distributed over the various co-products. This distribution is called allocation, and is one of the most complex components of LCA. The preferred practice in LCA is to avoid allocation wherever possible by expanding or sub-dividing the system boundary to obtain single-output processes (eg. expand to include the entire product system for a recycled material). Where allocation cannot be avoided, it should be done in a way that reflects the physical relationships between the process outputs, or if this is not feasible, in a way that reflects other (eg. economic value) relationships between them.

The most common LCA practice, and the one used here as the default method for co-product allocation, is to allocate on the basis of mass. However with this approach, the various co-products have the same numerical value for any particular impact category at the point in the production chain where the co-products are separated (eg. on exit from the Imperial Smelting furnace). The issue of co-product allocation is discussed in more detail later in the paper.

RESULTS

The results of the LCA study are summarised in Table 2. These results show that when lead and zinc are produced on their own (by the Blast furnace and Electrolytic processes respectively), zinc production is more than twice as energy intensive as lead production with a similar factor applying to the associated GWPs and APs. Zinc produced by the Electrolytic process is more energy intensive than zinc produced by the Imperial Smelting process due to the high electricity consumption of the electrolysis step in the former process and associated power plant generation inefficiencies. When produced jointly in the Imperial Smelting process, the two metals have not too dissimilar total energy consumptions and GWPs and APs.

Table 2. LCA results for the production of unit mass of lead and zinc.

Impact category	Zinc		Lead	
	Electrolytic	ISP	Blast furnace	ISP
Total energy (MJ/kg)	48	36	20	32
GWP (kg CO ₂ e/kg)	4.6	3.3	2.1	3.2
AP (kg SO ₂ e/kg)	0.055	0.036	0.022	0.035
Solid waste (kg/kg)	10.0	9.3	9.3	9.6
Liquid waste (kg/kg)	29.3	15.4	14.8	15.9

The reason lead produced by the Imperial Smelting process has a greater environmental impact than lead produced by the Blast furnace process is that it carries a penalty for being co-produced with zinc in the former process. As outlined earlier, this means that lead and zinc metal products exiting the Imperial Smelting furnace have the same numerical values per unit of metal for each of the impact categories (eg. 29.3 MJ/kg and 2.9 kg CO₂ e/kg for total energy and GWP respectively), with differences in the inputs to, and the performances of, the separate refining stages for each metal (see Table 1) giving rise to the final results tabulated in Table 2. The Electrolytic zinc process has higher liquid wastes than any of the other three processes due to the waste liquors associated with the electrolysis stage, while the solid waste emissions were similar for all four processes and consisted primarily of tailings solids followed by waste rock from the mineral processing and mining stages respectively, with slag wastes making a small contribution (less than 10% of total solid waste) in the case of the Imperial Smelting and Blast furnace processes.

The contributions of the various process stages to the overall GWP are shown in Figures 2 and 3 for the lead and zinc base cases respectively. It is apparent from these figures that the metal production and refining stages make the largest contribution for all processes considered. This result is not surprising, and reinforces the point made earlier that this stage generally involves chemical transformations requiring significant energy inputs.

The folly of not comparing processes on a life cycle basis is illustrated in Figure 4 where the direct (ie. consumed within the process) and indirect (ie. consumed outside the

process, eg. power generation) contributions towards the total energy consumption for the various processes are shown. The total process energy consumption on a life cycle basis is the sum of the direct and indirect contributions. It would be clearly misleading to compare the processes on a direct energy consumption basis only, as this would indicate, for example, that producing zinc by the electrolytic process is less energy intensive than producing it by the Imperial Smelting process, which on a life cycle basis, is clearly not the case

The electricity consumptions of the various stages of the various metal production routes are given in Table 3, with the data from Table 1 expressed in terms of per tonne of refined metal and allocated between the two co-products in the case of the Imperial Smelting process where appropriate. The sintering and acid plant stage consumes the largest proportion (in the order of 50-65%) of the electricity used in the Imperial Smelting and Blast Furnace processes, with the acid plant being responsible for the majority of this, while the combined roasting/leaching/electrolysis stage consumes the largest proportion (typically 90%) of the electricity used in the Electrolytic zinc process.

Table 3. Electricity consumption (kWh/t lead or zinc) for process stages.

Lead		Zinc	
<i>Imperial Smelting process</i>		<i>Imperial Smelting process</i>	
Mining	119	Mining	116
Mineral processing	58	Mineral processing	57
Sintering & acid plant	549	Sintering & acid plant	532
Imperial Smelting furnace	114	Imperial Smelting furnace	174
Refining	<u>3</u>	Refining	<u>25</u>
	<u>843</u>		<u>904</u>
<i>Blast Furnace process</i>		<i>Electrolytic process</i>	
Mining	111	Mining	127
Mineral processing	265	Mineral processing	305
Sintering & acid plant	590	Roasting/leaching/electrolysis	4000
Blast furnace	160		<u>4432</u>
Refining	<u>3</u>		
	<u>1129</u>		

Effect of ore grade

The effect of several process variables on the LCA results was also investigated. Figures 5 and 6 show the effect of ore grade (both lead and zinc) on the GWP for lead and zinc metal production by the Imperial Smelting process. As might be expected, the GWP for both metals increases as ore grade decreases (due to the greater amount of material that has to be treated in the mining and mineral processing stages per unit mass of metal), with the GWP for zinc being slightly higher than that for lead from the same process, as already mentioned, with the difference becoming more pronounced at the lower ore

grades. A similar result for the effect of ore grade was reported by Norgate and Rankin (2000) for copper and nickel production.

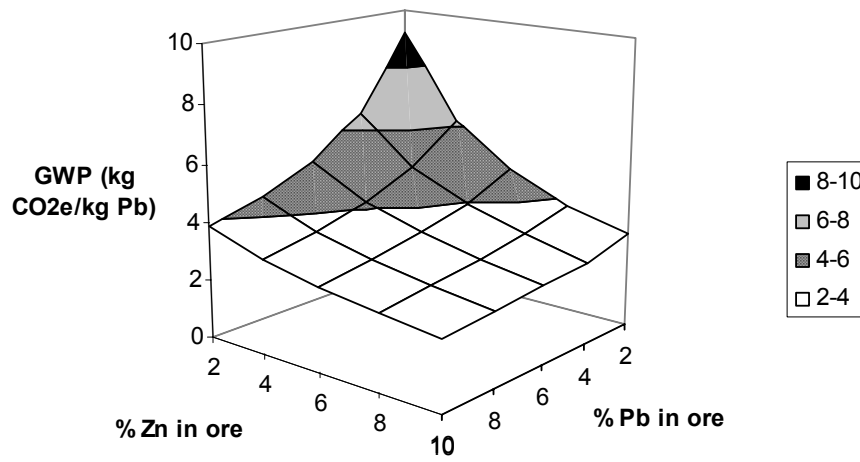


Fig. 5. Effect of ore grade on GWP for lead (Imperial Smelting process).

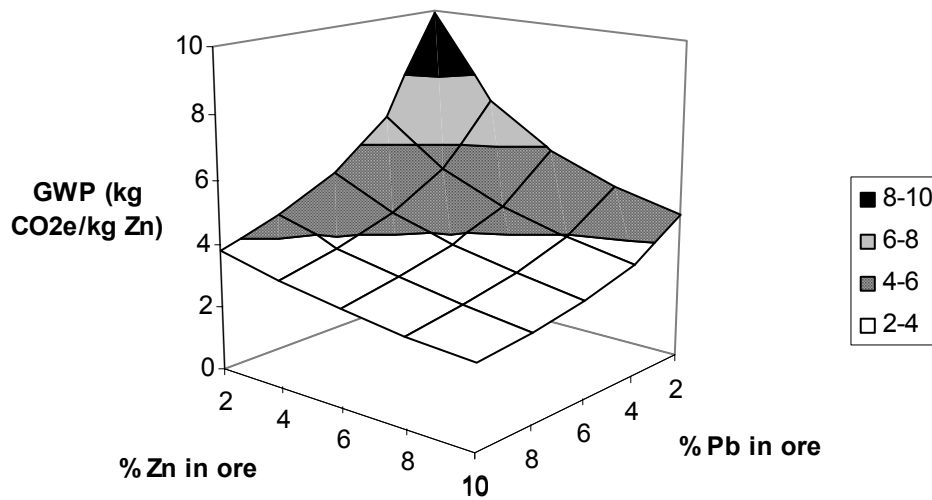


Fig. 6. Effect of ore grade on GWP for zinc (Imperial Smelting process).

Effect of fuel source and efficiency of power generation

Given the significant contribution of electricity consumption and associated power plant generation inefficiencies to the total energy consumption, GWP and AP of the various processes, in particular the Electrolytic zinc process, the effect of using natural gas and hydroelectricity instead of black coal as the fuel source for electricity generation, as well as the efficiency of generation, on the LCA results was investigated and the results are shown in Figures 7 and 8 for lead and zinc respectively. Hydroelectricity is often assumed not to be associated with any greenhouse gas emissions, however recent studies

(ACARP, 2000; Carvalho and Bizzo, 2000) have suggested that decaying vegetation submerged by flooding may give off appreciable quantities of greenhouse gases. The amount of greenhouse gases emitted from hydroelectric dams varies greatly, depending on climatic factors and the nature of the land that is flooded to create the dam. Based on data provided by these authors, a greenhouse gas emission value of 0.19 t CO₂e/MWh was used for hydroelectricity in this study. A generation efficiency of 80% was used for hydroelectricity (Briem et al, 2000).

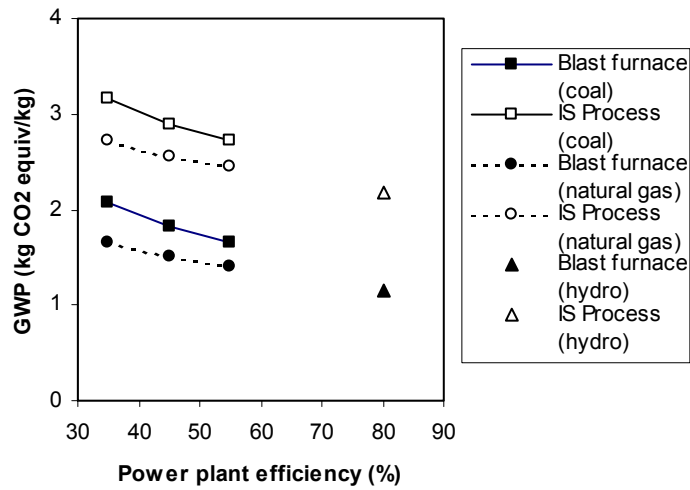


Fig. 7 Effect of fuel type and efficiency for electricity generation on GWP for lead.

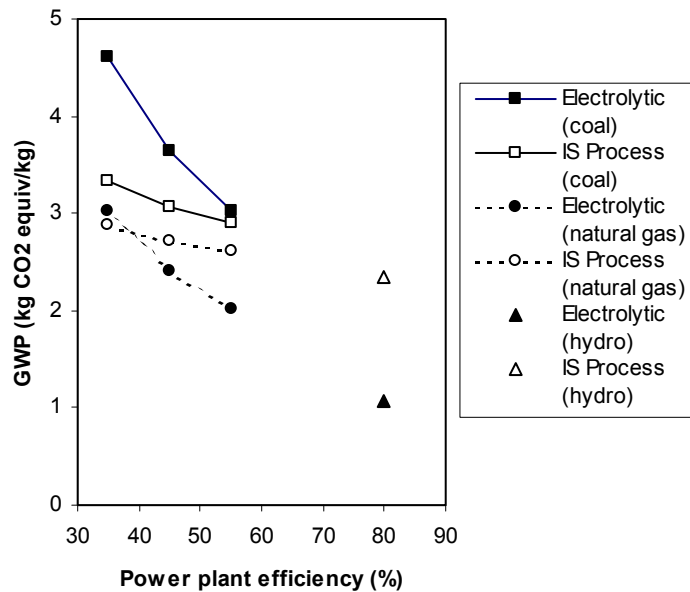


Fig. 8 Effect of fuel type and efficiency for electricity generation on GWP for zinc.

The use of natural gas-based electricity and hydroelectricity reduced the GWP of all processes, as both have lower greenhouse gas intensities than black coal-based electricity (0.57 t CO₂e/MWh, 0.19 t CO₂e/MWh and 0.96 t CO₂e/MWh for natural gas, hydro and black coal based electricity respectively). As is to be expected, increasing the power plant generation efficiency reduced the GWP in the case of black coal and natural gas based electricity, with the effect being greatest for the Electrolytic zinc process because of the high electricity consumption of this process.

DISCUSSION

The Imperial Smelting process is the only process of those considered that treats bulk concentrates, and hence there is no choice between the processes for treating bulk concentrates. Therefore while the environmental impacts of producing unit mass of lead and zinc by the various process routes were compared earlier in Table 2, it is also of interest to compare the total production of lead and zinc from bulk concentrate in the Imperial Smelting process with the production of the equivalent amount of lead and zinc by the Blast furnace and Electrolytic processes respectively. The bulk concentrate considered here for the Imperial Smelting process (35.3% Zn and 21.6% Pb as outlined earlier) produced metal co-products in the proportions 60% zinc and 40% lead. Combining the values in Table 2 in these proportions gives the results shown in Table 4 for total energy, GWP and AP, which indicates that for this particular bulk concentrate,

Table 4. LCA results for the production of 60% zinc and 40% lead metal co-products.

Impact category	ISP	Blast furnace & electrolytic processes
Total energy (MJ/kg Pb + Zn)	34.4	36.8
GWP (kg CO ₂ e/kg Pb + Zn)	3.3	3.6
AP (kg SO ₂ e/kg Pb + Zn)	0.036	0.042

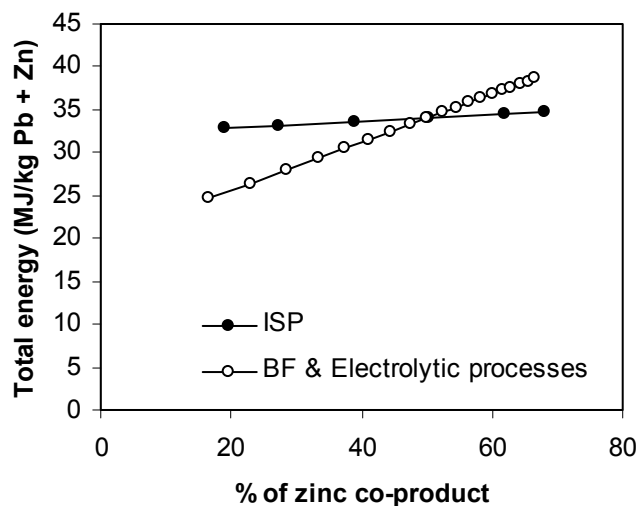


Figure 9. Total energy for combined lead and zinc production.

the production of lead and zinc by the Imperial Smelting process results in lower overall values for these three environmental impacts than does the production of the equivalent amount of lead and zinc produced separately in the Blast furnace and Electrolytic processes respectively. However this outcome is dependent on bulk concentrate grade, and only applies for grades that produce more than about 50% zinc metal co-product as shown in Figure 9. The Imperial Smelting process results in this figure were obtained by re-running that particular spreadsheet model for a number of different bulk concentrate grades, assuming as a first approximation, that the various process inputs shown in Table 1 were not significantly affected by bulk concentrate grade.

All the results for the Imperial Smelting process presented up to this point have been based on the default method of allocating the environmental impacts of the process to the co-products (lead bullion and crude zinc) in proportion to their masses (with equal weighting factors for both co-product masses). However a number of other allocation methods have been proposed (Burgess and Brennan, 2001; Weidema, 1997) and some of these are:

- allocation based on natural and physical relations of cause and effect (ie. causality)
- allocation based on avoided environmental impacts
- allocation based on the economic values of the co-products,

All of the methods have particular weaknesses (eg. allocation based on economic values involve prices which are themselves variable). Nevertheless, it is of interest to compare the environmental impacts of the Imperial Smelting process using the different allocation procedures outlined above.

Azapagic and Clift (1995) used so-called “marginal values” (ie. changes in a particular environmental impact with changes in the output of one co-product with the other co-products held constant) to allocate environmental impacts on a causality basis. By making small changes in the composition of the bulk concentrate to the ISP spreadsheet model (and assuming once again that these changes do not significantly affect the process inputs in Table 1) “marginal values” were calculated for the ISP. These values were then used as relative weighting factors for the co-product masses in allocating the various environmental impacts of the process. This method is in contrast with the default method referred to above, where the co-product masses were weighted equally.

While it is possible to consider two types of avoided impacts for the ISP co-products, viz. the lead co-product replaces lead produced by the Blast Furnace process, or alternatively the zinc co-product replaces zinc produced by the Electrolytic process, from a metallurgical point of view it is more appropriate to consider the former, as both lead products are pyrometallurgically based and furthermore, the two zinc products are not directly substitutable as indicated earlier. Thus the lead co-product was allocated the same environmental impacts as those calculated for the Blast Furnace process (Table 2), with the zinc co-product impacts being calculated by difference. For the case of allocation based on economic values, the prices of lead and zinc were taken as \$US480/t

and \$US970 respectively, and these values were used as relative weighting factors for the co-product masses, similar to the “marginal values” method above.

The environmental impacts of the Imperial Smelting process based on the different co-product allocation methods are compared in Table 5. It can be seen from this table that all three alternative methods give higher impacts for the zinc co-product and lower impacts for the lead co-product compared to the default mass-based (equal weighting) method. Even the impacts for the zinc co-product from the “avoided impact” method (highest of all three alternative allocation methods considered) are still below those for zinc produced by the Electrolytic process (Table 2). Arguments can be advanced for all of the methods included in Table 5. The “avoided impact” method more truly reflects the metallurgy of the process, as it is well known that it is easier to reduce lead than zinc – in fact lead is often regarded as getting a “free ride” in the Imperial Smelting process. However it might be argued that as lead cannot be produced from bulk concentrate in the Blast Furnace process, the concept of “avoided impact” (from treating bulk concentrate) does not apply in this case and that it should bear some of the additional environmental impacts of being co-produced with zinc in the Imperial Smelting process.

The most appropriate co-product allocation method to use for a particular case study is still the subject of much debate in the LCA literature, and in fact it has been suggested that a single solution to the allocation problem will probably never be agreed on (Burgess and Brennan, 2001). Allocating on the basis of economic value is reported to be increasingly used in Europe (Burgess and Brennan, 2001).

Table 5. Environmental impacts of the ISP for different allocation methods.

Impact category	Default (mass)		Marginal values		Economic values		Avoided impacts	
	Pb	Zn	Pb	Zn	Pb	Zn	Pb **	Zn
Total energy (MJ/kg)	32	36	28	39	28	39	20	44
GWP (kg CO ₂ e/kg)	3.2	3.3	2.6	3.7	2.7	3.6	2.1	4.0
AP (kg SO ₂ e/kg)	0.035	0.036	0.026	0.041	0.030	0.039	0.022	0.044
Solid waste (kg/kg)	9.6	9.3	8.0	10.2	8.2	10.1	9.3	9.5
Liquid waste (kg/kg)	15.9	15.4	13.6	16.8	13.6	16.8	14.8	16.1

** same as for Pb Blast Furnace

It is often difficult to compare the results from different LCA studies of the production of a particular metal, as issues such as ore grade, concentrate transport and fuel source used for electricity generation, among others, influence the results, even for the same process technology. Nevertheless broad comparisons can sometimes be made, and the results obtained in this work for total energy consumption of zinc production are compared in Table 6 with some results reported in the literature. There is broad agreement between all the results except for the results of Gediga et al (1997), however the reasons for this are unclear as the inventory data for this study were not reported.

While it may be possible to reduce the energy consumption (and hence the associated GWP and AP) of the various process steps in the metal production routes considered here by improved technology, there are natural limits on the extent of these reductions, eg. thermodynamic limits for electrowinning. Increased levels of metal recycling offer the

greatest potential for reducing the environmental impacts associated with metal production, and has been discussed in some detail by Norgate and Rankin (2002).

Table 6. Comparison of LCA results for total energy of zinc production (MJ/kg Zn).

	Imperial Smelting process	Electrolytic process
This work	36	48
Kellogg (1982)	38	50
Dove and Boustead (1998)	-	51
Reuter (1998)	41	41
Gediga et al (1997)	47	74

CONCLUSIONS

This “cradle-to-gate LCA of various processing routes for lead and zinc metal production based on average industry data derived from the literature has illustrated the importance of taking a life cycle approach when comparing the environmental impacts of different processes. Comparing the various processing routes for lead and zinc production has shown that:

- when lead and zinc are produced on their own (by the Blast Furnace and Electrolytic processes respectively), zinc production is more than twice as energy intensive as lead production,
- when produced jointly by the Imperial Smelting process, the two metals have not too dissimilar total energy consumptions based on the default allocation method (equal mass weighting),
- zinc production by the Electrolytic process is more energy intensive than that produced by the Imperial Smelting process due to the high electricity consumption of the former process and associated power plant generation inefficiencies,
- lead produced by the Imperial Smelting process is more energy intensive than that produced by the Blast Furnace process as it carries a penalty for being co-produced with zinc in the former process, based on the default allocation method (equal mass weighting) used,
- the Imperial Smelting process is the only one that treats bulk concentrates, and for bulk concentrates that produce more than about 50% zinc in the metal co-products, the combined production of lead and zinc by this process has a lower total energy consumption than does the production of the equivalent amount of lead and zinc by the Blast furnace and Imperial Smelting processes respectively, based on the default allocation method (equal mass weighting) used,
- of the three alternative co-product allocation methods (“marginal values”, “economic values” and “avoided impacts”), the latter is considered to be the one that most truly reflects the metallurgy of the Imperial Smelting process,
- the most appropriate co-product allocation method to be used for a particular case study is still open to conjecture, and indeed a single solution to the allocation problem may possibly never be agreed on,

- the GWP and AP results for the various processing routes by and large mirror the results for total energy as the energy inputs are fossil fuel based (coal or natural gas),
- the Electrolytic zinc process has higher liquid wastes than any of the other processes due to the waste liquors associated with the electrolysis stage,
- the solid waste emissions were similar for all processes and consisted primarily of tailings solids followed by waste rock from the mineral processing and mining stages respectively, with slag wastes making a small contribution (less than 10% of total solid waste) in the case of the Imperial Smelting and Blast furnace processes,
- the mining and mineral processing stages, which were common to all three processing routes, made only a small contribution to the environmental impacts examined, with the greatest contribution coming from the metal production and refining stages, however the former stages do make significant contributions to other environmental impacts such as acid mine drainage,
- declining ore grades will result in higher energy consumptions and gaseous emissions for all three processing routes due to the greater amount of material to be treated per unit mass of recovered metal,
- using natural gas instead of black coal as the fuel source for electricity generation will reduce greenhouse gas emissions as will an increase in power plant generation efficiency,
- hydroelectricity, while not greenhouse gas emission-free, will also reduce greenhouse gas emissions to values lower than that for natural gas-based electricity, but is not always an available option.

Because of differences in the operating performance of plants even using the same technology, the results reported here should be considered as indicative values only for the respective processes.

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