ALTERNATIVE ROUTES TO STAINLESS STEEL – A LIFE CYCLE APPROACH

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ABSTRACT

A Life Cycle Assessment (LCA) of stainless steel production, including that of the nickel, ferronickel, ferrochromium and iron feedstocks was carried out using inventory data derived from the literature. The environmental impact categories considered in the study were Global Warming Potential (GWP), Acidification Potential (AP) and total (or full cycle) energy consumption. The effects of different sources of electricity (black coal, natural gas and hydroelectricity) were also examined in the study.

The results of the LCA showed that when ferronickel is used as the nickel source, the total energy consumption for stainless steel production is approximately 50% higher than when nickel metal is used as the nickel source (75 MJ/kg cf. 49 MJ/kg). This result comes about largely because the Fe units in ferronickel have a much higher energy intensity than do the Fe units in pig iron, and the greater the use of the former at the expense of the latter, the greater is the total energy consumption. The results also showed that the production of ferronickel made by far the largest contribution (59%) to the total energy consumption for stainless steel production when this feedstock is used as the nickel source, but when nickel metal is used as the nickel source the contributions of the various stages are more evenly distributed.

It was also observed that the electricity consumption of the electric furnaces used in the production of ferronickel, ferrochromium and stainless steel contributed approximately 50% to the total energy consumed in stainless steel production. Given the relatively low efficiencies associated with electrical power generation, significant reductions in the total energy of stainless steel production could be anticipated if more direct use of thermal energy was made in the ferronickel, ferrochromium and/or stainless steel smelting stages, for example by utilising bath smelting processes.

1. INTRODUCTION

Sustainable development concepts have resulted in increasing environmental pressures to improve the efficiency of resource utilization and significantly reduce waste generation and emissions. These concerns have in turn focussed attention on the the supply chains and life cycles in which minerals and energy resource processing take part, as resource processing represents a particularly critical stage for the potential release of gaseous liquid and solid emissions, for it is here that chemical transformations often take place. However, given the large number of feed streams, by-product streams, waste streams and energy inputs associated with resource extraction and processing, evaluation of new or existing processes to attain these goals is not always a straightforward exercise. To obtain an accurate environmental picture of a process, it is essential that the process be evaluated over its entire life cycle. 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. LCA methodology is being used by CSIRO Minerals to examine various metal production processes practised either currently or potentially in Australia, with a view to assisting in the development of a sustainable mineral processing and metal production industry in Australia. Metals studied to date include copper and nickel [1], aluminium [2], lead and zinc [3] and titanium (unpublished).

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The push towards sustainable development is likely to see greater emphasis placed on dematerialisation, resulting in smaller and lighter products with longer service lives and produced with lower material and energy intensities. Indeed it is likely that low energy-intensive metals will replace high energy-intensive metals where any special properties of the latter (eg. light weight) are not particularly critical. Stainless steel is an obvious candidate to meet these needs as its excellent corrosion resistance affords it a long service life, as well as being a relatively low energy-intensive metal with few toxicity concerns. Over the last decade stainless steel production has experienced an annual growth rate of 5–7% worldwide [4] compared to 1.5% for carbon steel [5], with a Western World production of about 19 Mt of stainless steel in 2002 [6]. Given the likely growing importance of stainless steel in future metallic applications, a LCA study of stainless steel production was carried out, including the production of iron, nickel, ferronickel and ferrochromium feedstocks. The purpose of the study was to identify those stages in the stainless steel production life cycle that made the most significant contributions to the overall environmental impact of the production process and which could be the source of potential environmental improvements. The study also provided baseline environmental impact values for existing processes that could be subsequently used in evaluating alternative processing routes for stainless steel production.

2. SCOPE OF LCA

Because of the limited availability of suitable data for a full "cradle-to-grave" approach, together with time constraints for sourcing such data, the system boundary for the study described here was restricted to "cradle-to-gate", i.e., the processes have only been considered to the point where refined stainless steel is made available to the secondary manufacturing sector. It does not include the manufacture of downstream products, their use, end of life and scrap recovery schemes.

The environmental impact categories considered in the study were greenhouse and acidification gas emissions. These emissions are presented both on an individual gas basis and on an aggregated gas basis (Global Warming Potential (GWP) and Acidification Potential (AP) respectively). The total (or full-cycle) energy consumption was also reported for each process. While other environmental impact categories are also important in LCA studies, the data necessary to evaluate these impact categories are often not available in the literature. In the case of toxicity impact categories (human toxicity and eco-toxicity), there are also concerns that even when such data are available, they do not truly reflect what occurs in the environment [7]. The functional unit for the study was 1 kg of refined stainless steel, with all impacts being expressed per kg of refined stainless steel.

The following processing routes were considered in the LCA study:

- iron and steel production by the integrated steel route (Blast Furnace and Basic Oxygen Furnace)
- nickel metal production by flash smelting and Sherritt-Gordon refining
- ferrochromium production by the rotary kiln/arc furnace process
- ferronickel production by the rotary kiln/electric furnace process
- stainless steel production by the electric arc furnace/argon-oxygen decarburization (EAF-AOD) process

The feedstocks to each process and their compositions as used in the LCA study are given in Table 1.

Table 1. Processes and feedstocks included in the LCA study.

Metal	Feedstock		Process
Iron/steel	Iron ore	(64% Fe)	Blast furnace & Basic Oxygen furnace
Nickel	Sulphide ore	(2.3% Ni)	Flash smelting & Sherritt-Gordon refining
Ferrochromium	Chromite ore	(27.0% Cr, 17.4% Fe)	Pelletising/sintering/pre-reduction/ submerged arc furnace
Ferronickel	Laterite ore	(2.4% Ni, 13.4% Fe)	Rotary kiln / electric furnace
Stainless steel	Pig iron Ferrochromium Ferronickel Nickel	(94% Fe, 4.4% C) (55% Cr, 30% Fe) (23% Ni, 69% Fe) (100% Ni)	Electric arc furnace / argon oxygen decarburization

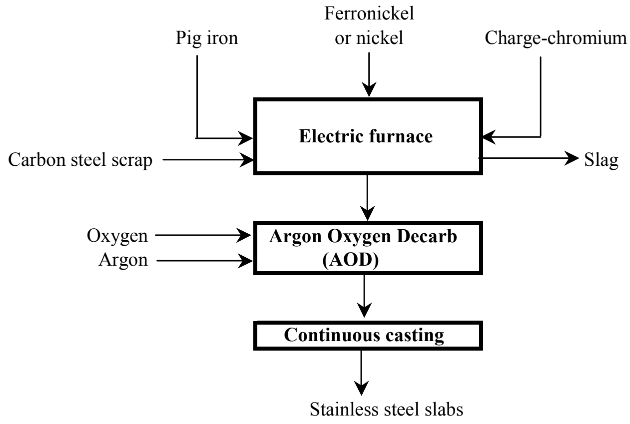

Figure 1. Schematic flowsheet of stainless steel production.

Stainless steels are typically produced by a two-stage process. Raw materials (including scrap) are melted together in an electric arc furnace, with the composition of the molten metal used corresponding approximately to that of the desired steel product, apart from the carbon content. The molten metal is then transferred to a refining vessel (most commonly an argon-oxygen decarburization (AOD) vessel) which reduces the impurities (especially the carbon content) to the low levels required in the final product.

A schematic flowsheet of stainless steel production by the electric furnace- argon/oxygen decarburization (EAF-AOD) process is shown in Figure 1. The compositions of the various metal inputs into this process given in Table 1 were used to estimate the required amounts of the various metal inputs to produce 304 stainless steel (which accounts for more than 50% of all stainless steels produced) with a composition of 68.6% Fe, 19.0% Cr, 9.3% Ni and 0.08% C. The estimated amounts of these various metal inputs using either nickel metal or ferronickel as the nickel source are given in the inventory table for stainless steel later in the paper. Process descriptions for the production of the various metallic feedstocks are given elsewhere, eg. ferronickel [8, 9], ferrochromium [8, 10], nickel [11, 12] and iron/steel [13].

3. ASSUMPTIONS AND INVENTORY DATA

The main assumptions made in regard to the ferrochromium, ferronickel and stainless steel production processes in carrying out the LCA were as follows:

General
- electricity is produced from black coal (Higher Calorific Value 30 MJ/kg)
- power station generation efficiency is 35%

Ferrochromium
- concentrator recoveries are 90% for Cr and 64% for Fe
- concentrate grade is 56% Cr_2O_3
- smelter recoveries are 79% for Cr and 94% for Fe
- ferrochromium alloy composition is 55% Cr, 7% C, 1.5% Ni and 30% Fe

Ferronickel
- smelter recoveries are 93% of Ni and 50% of Fe in the ore to ferronickel
- ferronickel composition is 23% Ni, 69% Fe, 1.9% C and 1.3% Cr

Stainless steel
- the stainless steel produced is grade 304 with composition 68.6% Fe, 9.3% Ni, 19.0% Cr and 0.08% C
- ratio of steel scrap to pig iron used is 0.054

LCA inventory data for the various metal production processes outlined above were sourced from the literature (and cross-checked with more than one source where possible) and are given in Tables 2-4 for ferrochromium, ferronickel and stainless steel respectively. Inventory data for the production of the other metallic feedstocks have been presented elsewhere, eg. nickel [1] and iron [14].

Table 2. Inventory data for ferrochromium production.

Stage	Inventory		
Mining	Electricity Diesel	2.2 0.001	kWh/t ore t/t ore
Mineral processing	Electricity	32	kWh/t ore
Smelting	Electricity Coke Limestone Water	2800 ** 4100 ** 0.56 0.25 10	kWh/t FeCr t/t FeCr t/t FeCr t/t FeCr

** Lower and upper limits.

Table 3. Inventory data for ferronickel production.

Stage	Inventory		
Mining	Electricity Diesel	3.9 0.0014	kWh/t ore t/t ore
Smelting - rotary dryer - rotary kiln - electric furnace	 Natural gas Natural gas Coal Electricity	 1.1 0.023 2.2 0.042 0.077 470	 GJ/t ore t/t ore GJ/t ore t/t ore t/t ore kWh/t ore

Table 4.Inventory data for stainless steel production.

Stage	Inventory		
EAF & AOD	*Ferronickel feedstock* Pig iron Ferronickel Charge chromium Carbon steel scrap *Nickel feedstock* Pig iron Nickel Charge chromium Carbon steel scrap Electricity Oxygen Argon Electrodes	 0.323 0.382 0.336 0.017 0.586 0..088 0.345 0.032 600 0.036 0.032 0.004	 t/t s steel t/t s steel t/t s steel t/t s steel t/t s steel t/t s steel t/t s steel t/t s steel kWh/t s steel t/t s steel t/t s steel t/t s steel
Continuous casting	Electricity	25	kWh/t s steel

4. RESULTS

Individual LCA spreadsheet models of the various metal production processes outlined in Table 1 were set up using the CSIRO Minerals in-house LCA software LCA-PRO (Excel-based). The relevant inventory data in Tables 2-4 were incorporated into the respective models and the results generated by the models are summarised in Table 5. It should be noted that the results for ferrochromium in this table correspond to the mean (viz. 3450 kWh/t) of the smelting electricity inputs of 2800 and 4100 kWh/t ferrochromium in Table 2. The results in Table 5 show that stainless steel produced using ferronickel as the nickel source has a total energy consumption of 75 MJ/kg while stainless steel produced using nickel metal as the nickel source has a total energy consumption of 49 MJ/kg.

The higher total energy consumption using ferronickel feedstock comes about because the total energy consumption for ferronickel production is 110 MJ/kg (column 5 in Table 5) which means that the nickel and iron units in the ferronickel both have an energy intensity of 110 MJ/kg (Fe or Ni) when the ferronickel total energy is allocated to the two metallic components on an equal-weighting mass basis (the most common LCA approach and the method used in this study). On the other hand, iron units in pig iron have an energy intensity of only 22 MJ/kg Fe (column 2 in Table 5). Thus when nickel metal is used as the nickel source, the amount of pig iron used is much greater (viz. 0.586 – 0.323 = 0.263 t/ t stainless steel from Table 4) and this results in an energy reduction of 0.263 x (110 – 22) = 23 MJ/kg, representing the majority of the difference in total energy given above (viz. 75 – 49 = 26 MJ/kg stainless steel). The nickel units in the stainless steel have little influence on this comparison as they have similar energy intensities in both feedstocks, viz. 110 MJ/kg Ni in ferronickel and 114 MJ/kg Ni in nickel metal (column 3 in Table 5).

The contributions of the various process stages to the total energy consumption and GWP for stainless steel production using either ferronickel or nickel metal as a feedstock are shown in Figures 2 and 3 respectively. It can be seen from Figure 2 that when ferronickel is used as the nickel source, the production of ferronickel makes by far the greatest contribution (56%) to the total energy consumption, while when nickel metal is used as the nickel source, the contributions of the various process stages are more evenly distributed, with ferrochromium production making the largest contribution (39%). The process stage contributions for GWP and AP (not shown) essentially mirror those for total energy as all energy used is fossil fuel based.

Table 5. LCA results for stainless steel production.

Environmental impact	**Feedstock materials for stainless steel production**				**304 Stainless steel**	
	Iron	Nickel	Ferrochrome	Ferronickel	From nickel	From ferronickel
Total energy (MJ/kg)	22	114	56	110	49	75
Gaseous emissions						
CO_2 (kg/kg)	2.0	11.1	5.1	8.9	4.8	6.6
CO (g/kg)	1.9	2.9	5.4	5.6	3.4	4.7
N_2O (g/kg)	0.02	0.05	0.06	0.07	0.04	0.06
CH_4 (g/kg)	2.6	16.6	6.2	18.4	6.0	10.8
NOx (g/kg)	12.6	44.6	29.6	70.6	24.8	44.1
NMVOC ** (g/kg)	0.20	2.7	0.17	1.6	0.4	0.8
SO_2 (kg/kg)	0.007	0.107	0.018	0.026	0.022	0.020
GWP (kg CO_2e/kg)	2.1	11.4	5.3	9.3	4.9	6.8
AP (kg SO_2e/kg)	0.015	0.138	0.039	0.075	0.039	0.051

** Non-Methane Volatile Organic Compounds

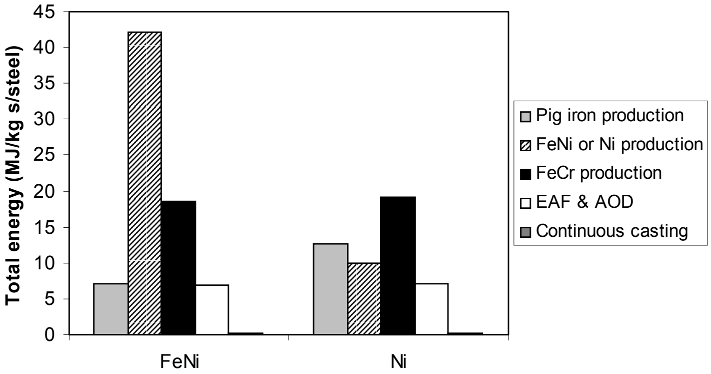

Figure 2. Stage contributions to total energy for stainless steel production.

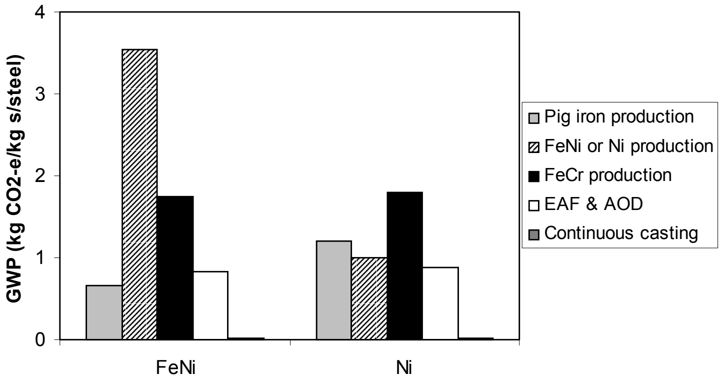

Figure 3. Stage contributions to GWP for stainless steel production.

5. DISCUSSION

Differences in factors such as ore grade, process technology, fuel source for electricity generation and transportation issues often make it difficult to compare the results from different LCA studies. Nevertheless broad comparisons can sometimes be made, and the results obtained in this LCA study for total energy consumption and GWP are compared with some other results reported in the literature in Table 6.

The results for iron/steel, ferrochromium and stainless steel (from ferronickel) in this table from this LCA study are not too different from the reported literature values. In the case of ferrochromium, the reported literature results are from an LCA study by the International Chromium Development Association [18] which used a smelting electricity consumption value closer to the upper limit given in Table 2. In view of this, it is more appropriate to compare the literature values for total energy and GWP with the results for the smelting electricity upper limit case (4100 kWh/t) shown in Table 6.

In the case of nickel and ferronickel, there is a much larger difference between the results of this LCA study and the literature values. However, the Nickel Development Institute (NDI) results are the average of both pyrometallurgical and hydrometallugical processing of both sulphidic and oxidic ores, whereas only pyrometallurgical processing of sulphidic ore was considered in the present LCA study. It has been shown previously [1] that hydrometallurgical processing has a higher total energy consumption than does pyrometallurgical processing for nickel metal production, which is consistent with the NDI results. These differences further illustrate the difficulty in comparing the results from different LCA studies.

Table 6. Comparison of LCA results for total energy and GWP with literature data.

Metal	**Total energy (MJ/kg)**	**GWP (kg CO_2e/kg)**
Iron		
This work	22	2.1
Steel		
This work	23	2.3
ACARP [14]	25	2.3
Brooks & Subagyo [15]	20–50	
Kellogg [16]	27	
Ferronickel		
This work	110	9.3
Nickel Development Institute [17]	225	
Nickel		
This work	114	11.4
Nickel Development Institute [17]	262	
Kellogg [16]	164	
Ferrochromium		
This work	56 [1]	5.3 [1]
	62 [2]	5.9 [2]
International Chromium Development Association [18]	71	6.0
Stainless steel		
This work - from ferronickel	75	6.8
- from nickel	49	4.9
Boustead & Hancock [19]	80	

1. Results for mean (3450 kWh/t) smelting electricity consumption
2. Results for upper limit (4100 kWh/t) smelting electricity consumption

The LCA results in Table 6 include both "direct" (from within the process) and "indirect" (external to the process) contributions – this is in fact the essence of the life cycle approach. The "direct" CO_2 contribution (from coke and limestone – see Table 2) for ferrochromium production obtained in this study was 1.6 kg CO_2e/kg ferrochromium and compares with values of 1.2 and 1.3 kg CO_2e/kg ferrochromium reported in the literature [20, 21]. The sum of the "direct" and "indirect" contributions was 5.1 kg CO_2e/kg ferrochromium (out of a total GWP of 5.3 kg CO_2e/kg ferrochromium) and the significant difference between these two values (viz. 1.6 and 5.1 kg CO_2e/kg ferrochromium) highlights the importance of comparing processes on a life cycle basis if an accurate environmental picture is to be obtained.

As the production processes for ferronickel, ferrochromium and stainless steel all involve electric furnaces, it is of interest to quantify the contributions that the electricity consumptions of these furnaces make to the total energy consumption for stainless steel production. The individual contributions and their total are shown in Figure 4, which indicates that the electricity consumption of these three furnaces contributes approximately 50% towards the total energy consumption for stainless steel production. Given the inefficiencies associated with converting thermal energy to electrical energy (35% conversion efficiency assumed in this study), a significant reduction in the total energy of stainless steel production could be anticipated if more direct use was made of the thermal energy in the respective smelting steps, for example by utilising bath smelting processes. As a simple illustration of this point, if the electrical energy contribution of ferronickel (26%) shown in Figure 4 could be replaced by direct thermal energy, a reduction in the order of 17% (viz. 0.65 x 26) in the total energy consumption for stainless steel consumption could be anticipated.

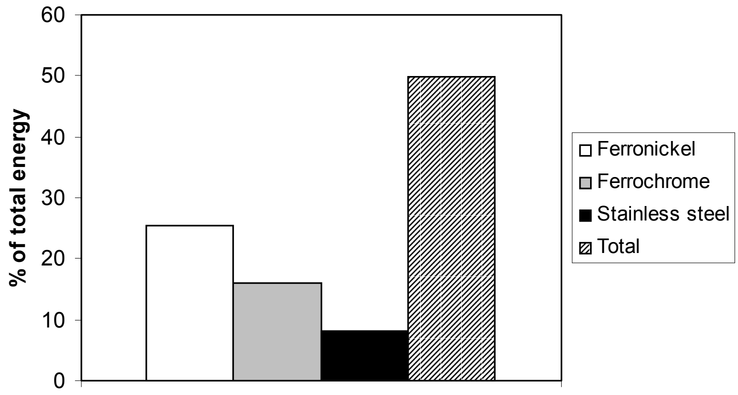

Figure 4. Contribution of electric furnaces to total energy consumption.

The effect of changing the source of the electricity consumed in the various processes and its associated generation efficiency was also examined in the study. Three differently derived types of electricity were considered:

- black coal at 35% generation efficiency (base case)
- natural gas at 35% generation efficiency (Higher Calorific Value 53 MJ/kg)
- hydroelectricity at 80% generation efficiency [12]

Hydroelectricity is often assumed not to be associated with any greenhouse gas emissions, however recent studies [14, 23] 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 190 kg CO_2-e/MWh was used for hydroelectricity in this study. The effects of electricity source on the total energy and GWP of stainless steel production using the two nickel feedstocks (ferronickel and nickel metal) are shown in Figures 5 and 6 respectively. Natural gas-based electricity reduced the GWP in both cases due to its lower greenhouse gas intensity (570 kg CO_2-e/MWh) compared to that of black coal (960 kg CO_2-e/MWh), but the total energy was unchanged as the generation efficiency remained at 35%. Hydroelectricity on the other hand, reduced both the GWP (due to its lower greenhouse gas intensity given above) and the total energy due to its higher generation efficiency (80% cf. 35%).

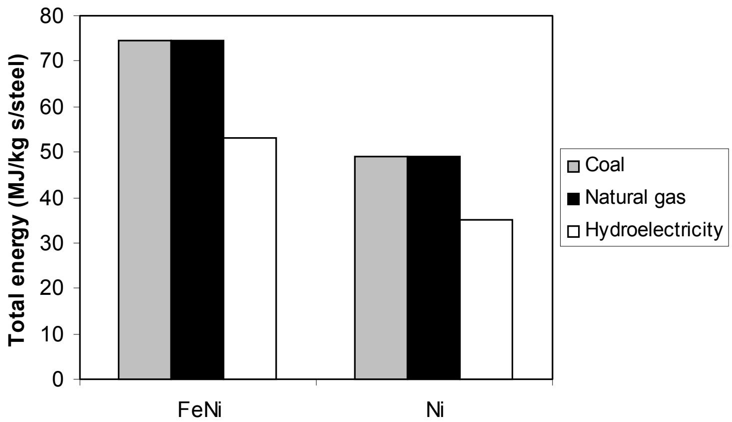

Figure 5. Effect of electricity source on total energy for stainless steel production.

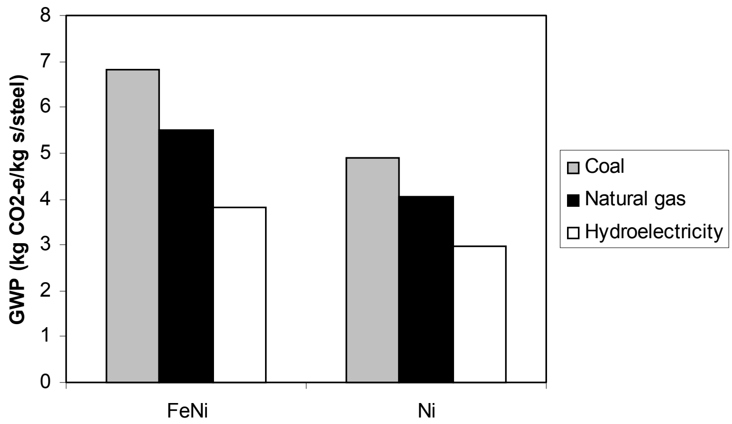

Figure 6. Effect of electricity source on GWP for stainless steel production.

The energy intensity of stainless steel production relative to the production of a number of other metals is shown in Figure 7 where the results from this LCA study are compared with the results from previous LCA studies by the authors [1, 2, 3]. It can be seen from this figure that the energy intensity of stainless steel is comparable with that for copper and zinc, lower than that for aluminium and nickel, but higher than that for steel and lead. Toxicity concerns often associated with copper and lead [7] and the generally shorter life span of steel compared to stainless steel due to its lower corrosion resistance, means that when all three factors (energy intensity, toxicity and lifespan) are considered together, stainless steel is probably the most suitable candidate of all the metals shown in Figure 7 for meeting sustainable development goals. However it should be borne in mind that the results shown in Figure 7 are for the cradle-to-gate stage only of the metals' life cycle. Subsequent downstream use of the metals has not been considered here. Inclusion of the latter stage ("gate-to-grave") will have a significant effect on the comparative environmental impacts of some metals. For example, the use of light metals in transport applications (such as vehicle manufacture) could significantly reduce life cycle energy consumption and greenhouse gas emissions associated with these applications [24].

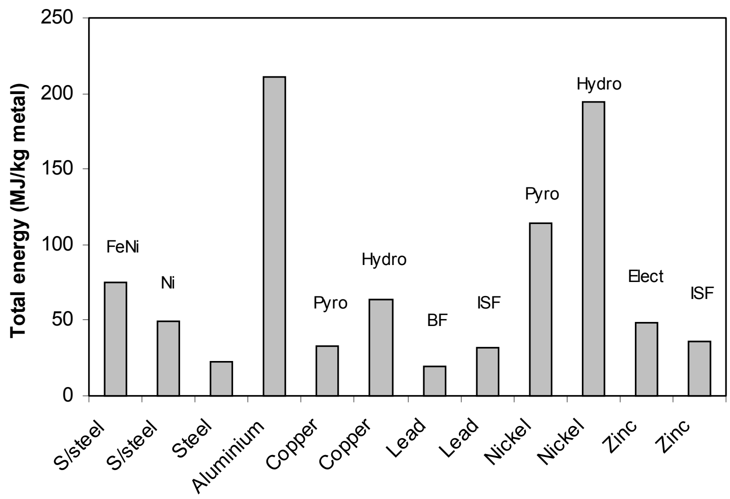

Figure 7. Total energy consumption for stainless steel production compared to other metals.

The energy intensity of the pyrometallurgical processes in Figure 7 can potentially be reduced in a number of ways, including:

- eliminating the need to reheat the feed materials into the process
- recovering the thermal energy contained in the slag products and utilising this energy within the process.

Using the stainless steel LCA model in conjunction with process simulation software, it was estimated that 1.4 MJ/kg stainless steel (400 kWh/t) would be saved by removing the need to reheat the feed materials shown in Figure 1. This saving constitutes two-thirds of the electricity input shown in Table 4, with the total energy consumption and GWP shown in Table 5 both being reduced by approximately 6% to 71 MJ/kg and 6.4 CO_2 e/kg respectively (with ferronickel feedstock), bearing in mind the electricity generation efficiency of 35%.

There have been only limited attempts to recover the thermal energy contained in slags, with the intermittent nature of slag availability complicating the engineering of any heat recovery system. Technologies for heat recovery from slag include:

- air heating (eg. from dry granulation)
- steam generation

Akiyama et. al. [25] also proposed a number of chemical heat recovery schemes that utilize chemical reaction heat instead of the sensible and latent heat schemes above. The stainless steel LCA model gave a result of 2.9 t slag/t stainless steel (including slags from iron, ferronickel and ferrochromium production). Assuming the various slags are all tapped at a temperature of about 1500 °C and cooled to 500 °C in some heat recovery system with a recovery efficiency of 50%, the potential heat that could be recovered was estimated at 0.75 MJ/kg of slag or 2.2 MJ/kg of stainless steel. This further reduces the total energy for stainless steel production (ferronickel feedstock) in Table 5 to 69 MJ/kg.

If the energy intensity of stainless steel production relative to the other metals in Figure 7 could be reduced even further, it would enhance stainless steel's attractiveness from a sustainable development viewpoint. As mentioned earlier, this may be possible by more direct use of thermal energy in the smelting stages used to produce the various metallic feedstocks. Work is currently in progress at CSIRO Minerals to investigate the use of bath smelting processes for more direct routes to stainless steel. The LCA results presented in this paper will be used to assess these alternative routes for the production of stainless steel.

6. CONCLUSIONS

A Life Cycle Assessment of stainless steel production using either ferronickel or nickel metal as the nickel feedstock has been carried out using inventory data derived solely from the literature. The following conclusions were drawn from this study:

- stainless steel produced using ferronickel as the nickel source had a total energy consumption of 75 MJ/kg compared to 49 MJ/kg for stainless steel produced using nickel metal as the nickel source
- the significant difference in total energy consumption between the two nickel feedstocks comes about because the Fe units in the ferronickel have a higher energy intensity (110 MJ/kg Fe) than do the Fe units in pig iron (22 MJ/kg Fe), and the greater the use of the latter in place of the former, the greater is the reduction in total energy
- the Ni units in ferronickel and nickel metal have similar energy intensities (110 MJ/kg Ni and 114 MJ/kg Ni respectively) and so do not have much of an influence on this comparison between the two feedstocks
- the GWP of stainless steel production from ferronickel is 6.8 kg CO_2-e/kg while from nickel metal it is 4.9 kg CO_2-e/kg, with the corresponding AP values being 0.051 kg SO_2-e/kg and 0.039 kg SO_2-e/kg
- when ferronickel is used as the nickel feedstock, the production of this material makes by far the largest contribution (56%) to the total energy consumption for stainless steel production
- on the other hand when nickel metal is used as the nickel feedstock, the contributions of the various process stages to the total energy consumption are more evenly distributed, with ferrochromium production making the largest contribution (39%)
- changing from black coal-based electricity to natural gas-based electricity (at the same generation efficiency of 35%) reduced the GWP of stainless steel production by about 18% for both ferronickel and nickel metal feedstocks
- changing from black coal-based electricity to hydroelectricity (at its reported generation efficiency of 80%) reduced the GWP of stainless steel production by about 40% and the total energy consumption by about 28% for both ferronickel and nickel metal feedstocks

- given the significant (approximately 50%) contribution of the electricity consumptions of the electric furnaces used in the production of ferronickel, ferrochromium and stainless steel towards the total energy consumed in the production of stainless steel, a substantial reduction in this total energy could be anticipated if more direct use was made of the thermal energy in the respective smelting steps, for example by utilising bath smelting processes.
- the energy intensity of metals produced by pyrometallurgical routes can potentially be reduced by eliminating the need to reheat the feed materials into the process and by utilising the thermal energy contained in the slag products within the process, with a potential reduction of 8% being indicated for stainless steel (with ferronickel feedstock)
- when issues such as energy intensity, toxicity and life span are considered together, stainless steel is observed to be one of the more suitable metals for meeting sustainable development goals, and could become even more attractive if attempts to reduce the energy intensity of its production are successful.

It is re-emphasised that the inventory data used for the various processes in this LCA study were derived solely from the literature, and as such, the results presented in this paper should be considered as indicative values only for the various metal production routes considered.

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