



Assessing the energy and greenhouse gas footprints of nickel laterite processing

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ABSTRACT

The energy and greenhouse gas footprints of some of the various technologies that are used for processing nickel laterite ores have been assessed using life cycle assessment methodology based largely on publicly reported inventory data. The results of the study were used to identify opportunities to improve the energy and greenhouse gas impacts of the various processes and to examine how they might be affected under different future scenarios such as falling laterite ore grades and the possible imposition of a carbon tax. The opportunities identified included the use of biochar as a fuel and reductant, along with slag waste heat recovery in ferronickel smelting, and the use of the emerging bath smelting technology for ferronickel production instead of the rotary kiln/electric furnace process. As a significant amount of the life cycle-based greenhouse gas emissions from the hydrometallurgical acid leaching processes are generated by acid neutralisation with lime or limestone, there may be opportunities to reduce these emissions by utilising other neutralising agents or possibly by considering non-acid leaching systems. Improving the energy efficiency of the electrowinning stage used to recovery nickel metal from the leach liquor is another possible way in which the sustainability of hydrometallurgical production of nickel from laterite ores could be improved.

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1. Introduction

Nickel is commonly present in two principal ore types – sulfide and laterite ores. Historically, most nickel production has been derived from sulfide ores. While about 70% of the world land-based nickel resources are contained in laterites, they currently account for only about 40% of world nickel production. The major reason for this is the difficulty of processing nickel laterites compared to sulfides – laterite ores require extensive and complex treatment to extract nickel, and have historically been more expensive than sulfide ores. This comes about largely because laterites, unlike sulfides, cannot be significantly upgraded or concentrated prior to processing, as the distribution of nickel throughout the molecular lattice of the particles makes the production of a concentrate by flotation or gravity separation impractical. This essentially means that nearly every tonne of laterite ore mined must be put through the entire process, resulting in intrinsically high capital and operating costs. However, there are two important benefits of laterite ores – they contain valuable cobalt and, being closer to the surface, can be processed by open-cut mining. There have been only a limited number of operational mining projects extracting laterite ores, and most have had major technical and financial difficulties that took several years to resolve satisfactorily (e.g. Moa Bay in Cuba).

Global nickel production has increased from some 10,000 tonnes of nickel in 1900 to about 1.6 million tonnes in 2008, with production increasing significantly since 1950 at a rate of about 4.7% per year (Mudd, 2010; Jessup and Mudd, 2008). Significant growth in laterite production will be required to balance the long-term supply of nickel as sulfide production falls off for reasons including:

- major sulfide regions (e.g. Western Australia) already optimised;
- limited new sulfide discoveries of significance in recent past.

The future supply of primary nickel metal will require the development of complex laterite-based projects with higher capital, technical, environmental and operating costs risks. However, increasing focus on sustainability issues in the minerals and metal production industry because of its visible, and not insignificant environmental footprint, means that the sustainability of these processes must be assessed at the earliest possible stage in their development. Life cycle assessment (LCA) is a methodology that has been developed in recent years that can be used for this purpose (Norgate et al., 2007a).

The life cycle-based energy consumption (i.e. embodied energy) of nickel production from laterite ores is significantly higher than that from sulfide ores (Mudd, 2010; Eckelman, 2010; Jessup and Mudd, 2008; Norgate et al., 2007a). Some reasons for higher energy requirements for laterites include:

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- laterites not significantly upgraded or concentrated prior to processing as noted above, hence virtually all of the ore goes to the energy-intensive metal extraction stage or parts thereof – e.g. all of the ore goes through the rotary kiln/electric furnace for ferronickel production, while for the high pressure acid leach (HPAL) process all of the ore goes through the leaching stage;
- differences in ore grade – laterites generally have lower grades than sulfides – hence more ore must be processed to produce the same amount of nickel metal;
- sulfur in sulfides acts as a fuel source – not present in laterites.

However, while comparisons of LCA results between nickel sulfides and laterites show distinct differences for the reasons outlined above, comparisons between the LCA results of the various laterite processing routes reported in the literature have a greater degree of uncertainty, even for the same processing route. There are a number of reasons why these differences occur, including:

- variation in ore mineralogy and moisture content, e.g. arid versus tropical laterites;
- technology variations, e.g. product – nickel metal, mixed sulfide, mixed hydroxide;
- process variables, e.g. high pressure acid leaching (Razavimanesh et al., 2006) including:
 - % solids in autoclave;
 - method of heating autoclave (direct or indirect);
 - autoclave pressure;
- different functional units, i.e. results may not all be expressed per unit mass of refined nickel metal – some may be expressed per unit mass of intermediate product (mixed hydroxide or sulfide) or per unit mass of nickel in the intermediate product or in the final product, e.g. ferronickel;
- co-product allocation may or may not have been used in calculating the results;
- differences in nickel laterite ore grade – as no laterite concentrate is produced the metal extraction and refining stages are directly affected by ore grade, unlike pyrometallurgical sulfide processing where only the mining and mineral processing stages are basically affected by ore grade;
- source of inventory data used – e.g. date, publicly available;
- whether the sulfur fuel energy has been included if the operation has an on-site acid plant;
- whether the feedstock energy of natural gas used in any on-site hydrogen plant has been included;
- whether or not electrical energy is converted to primary energy, and if so, what thermal efficiency is used, e.g. ferronickel production using electric furnaces;
- in addition to the above factors, reported greenhouse gas emissions are also affected by the greenhouse gas emission factors used for a particular energy source, e.g. electricity grid fuel mix.

In this paper the authors have attempted to compare the energy and greenhouse gas footprints of the various processing routes for nickel laterites by taking a life cycle approach while at the same time eliminating or reducing a number of the factors outlined above in order to make the LCA results more comparable between processes. While there are three components of sustainability, namely, environment, economics and society, the focus here is on the environmental aspect, in particular energy and greenhouse gas emissions. Other environmental issues such as water, solid wastes, waste toxicity, effluent treatment, tailings disposal and post-mining rehabilitation will also have to be addressed in due course.

2. Laterite mineralogy and resources

Nickel laterite ores are categorised into two types – limonite ore and saprolite ore, as mentioned above. The two fractions are found together, with the limonitic portion generally overlaying the saprolite. In reality, there is no clear-cut boundary between the two ores and they are intermingled, especially in the so-called “transition” zone between the two layers. This is to be expected as these ores are formed by gradual leaching of low grade ultramafic rocks by rain water, with limonite being in the more advanced state of transformation (Stadelhofer et al., 2009). The different regions in a laterite ore are classified (Whittington and Muir, 2000) as follows:

- upper overburden (Ni < 1%);
- limonite layer (Ni ~ 1.4%, SiO₂ ~ 6%, MgO ~ 3%, Co ~ 0.15% and Fe > 40%);
- possibly a transition layer (1.5–2.4% Ni);
- saprolite layer (Ni ~ 2.4%, SiO₂ ~ 38%, MgO ~ 25%, Co ~ 0.05% and Fe < 15%);
- lower base rock layer.

The environment in which the laterisation process occurs (e.g. the type of parent rock, the climate in which the deposit was formed and the weathering history) influences the laterite mineralogy. Commercially viable nickel laterites generally do not contain discrete nickel minerals. Most laterite deposits occur in tropical and sub-tropical regions, with “wet” and “dry” laterite deposits in tropical and sub-tropical areas respectively. There are abundant nickel resources known around the world, principally in Australia, Canada, New Caledonia, Phillipines, Indonesia and Russia, amongst others. According to Dalvi et al. (2004), global resources of laterite ores are 12,600 million tonnes (containing 161 million tonnes of nickel), with almost twice as much laterite resource amenable to hydrometallurgical processing than is amenable to pyrometallurgical processing. Since laterite type ores naturally occur close to the surface, open-pit mining methods are generally used to recover the ore after removal of the overburden. Laterite deposits typically occur in layers up to 40 m in depth below the surface. Selective mining principles are applied where feasible so that the nickel laterite layers are mined as separately as possible. For example, at the Goro mine in New Caledonia, the limonite and saprolite ores are extracted separately from a series of terraces using hydraulic excavators and bulldozers.

3. Processing of nickel laterites

The first processing treatment for recovering nickel from laterites was developed in 1879 in New Caledonia, based on the iron blast furnace technology of the day. Processing of nickel laterite ores utilises a variety of technologies, including:

- ferronickel smelting;
- nickel matte smelting;
- blast furnace/electric furnace (nickel pig iron) smelting;
- high pressure acid leach (HPAL);
- atmospheric leaching (AL);
- enhanced pressure acid leach (EPAL), i.e. HPAL and AL combined;
- heap leaching (HL);
- sulphation atmospheric leach (SAL);
- Caron process.

However, the above technologies are in various stages of development, with not all being commercialised as yet, particularly some of the hydrometallurgical processes.

Because laterites contain no sulfur, the principal process route in the past has been a reduction roast, followed by an ammonium carbonate leach (the Caron process). However, one problem with roasting is that much of the cobalt is lost in the leach residue (Parkinson, 1999). The pyrometallurgical process for refining saprolite ores and the acid leach process both recover more nickel from the ore than the Caron ammonia leach process. The acid leach process is additionally favoured over the Caron process due to the high cobalt content of limonite ore, the high cobalt recovery (>90%), lower energy requirements and lower capital costs (Whittington and Muir, 2000). Furthermore, acid pressure leaching plants can use relatively inexpensive elemental sulfur to make acid for the leach process and to produce heat for high-pressure steam. However, acid leaching is not very economic at processing ores containing acid consuming compounds, such as magnesia, since acid consumption is the highest cost component in the acid leach process (Whittington and Muir, 2000). It is generally considered that saprolite ores, which have a high nickel, magnesium and silica content, are best processed by pyrometallurgical processes. Both the pyrometallurgical and hydrometallurgical processes can accept ore from the transition layer between the upper limonite layer and the lower saprolite layer. The geothite-rich limonite ore has a relatively low nickel content but a high iron and cobalt content and is mainly processed by hydrometallurgical methods. Generalised flowsheets for the three laterite processing routes are shown in Fig. 1. The choice of technology for the treatment of nickel laterite ores is generally driven by project-specific parameters, which is one reason why there are many different processing options used in current operating and proposed plants. Dalvi et al. (2004) provide a summary of 28 laterite operations (past and present) dating back to the 1940s. The sustainability assessment of nickel laterite processing described in this paper did not consider the nickel pig iron smelting and sulfation acid leach processes.

3.1. Pyrometallurgical routes

Silica and magnesia-rich saprolite ores can be processed pyrometallurgically by either minimising the Fe/Ni ratio and refining a ferronickel product or adding sulfur to form a nickel/iron sulfide matte which can be refined further. The ferronickel process in-

volves calcining and pre-reducing the ore at 850–1000 °C in a rotary kiln, then smelting at 1500–1600 °C in an electric furnace in the presence of carbon to separate the nickel/iron-containing phase from the silica–magnesia slag. According to Dalvi et al. (2004):

- high carbon ferronickel is best produced from those ores with a high nickel grade (>2.2% Ni), low Fe/Ni ratios (5–6) and high MgO – examples of these operations are Japanese ferronickel smelters;
- low carbon ferronickel can be produced from saprolitic ores with generally >1.5% Ni and relatively high Fe/Ni ratios (6–12) and high melting point slag (either high MgO – example Falcondo, or high SiO₂ – example Cerro Matoso);
- matte smelting is more suited to ores with relatively high Fe/Ni ratios (>6) and lower melting point slag (<1600 °C) – SiO₂/MgO ratio between 1.8 and 2.2 – example PT Inco.

In the ferronickel process, run-of-mine saprolite ore is dried and fed into a rotary kiln along with a solid reducing agent, mainly coal, and the ore travels through the kiln in a counter-current mode. Remaining free moisture and bound water is evaporated and the saprolite ore is partially reduced, mainly iron oxide Fe³⁺ to Fe²⁺ but also up to 20% oxidic nickel to metallic nickel. At the end of the process the pre-reduced material exits the kiln at a temperature of about 700–1000 °C. The majority of the reduction and smelting is carried out in a subsequent electric arc furnace (EAF). The reduction conditions in the EAF are controlled by the amount of remaining coal in the hot feed and the carbon uptake from the electrodes. Basically all nickel oxide is reduced to nickel metal as well as all remaining Fe³⁺ to Fe²⁺. More severe reducing conditions lead to lower grades of ferronickel (10–15% Ni), while with less severe reducing conditions a higher grade of ferronickel (>30% Ni) can be achieved. Solar et al., 2008 carried out an analysis to determine the economically optimum ferronickel grade for a typical high grade saprolite ore and showed that the most important factor in determining the optimum ferronickel grade is the value received for its iron content. For typical iron credits, the optimum ferronickel grade was in the order of 35% nickel, indicating that nickel laterite smelters should favour low reductions. In a world survey of nickel laterite smelters Warner et al. (2006) reported that about 30% of world primary nickel production was produced from laterites by pyrometallurgical routes, with ferronickel being the predominant product (approximately 72%).

3.2. Hydrometallurgical routes

The nickel and cobalt bound within the geothite or clays can be released from the solid matrix by acid leaching. The soluble iron species subsequently hydrolyse to basic iron sulfates which under the conditions present in the pressure leach (temperatures greater than 200 °C), react to hematite and regenerate acid (Whittington and Muir, 2000). Atmospheric leaching of laterite ores can extract significant nickel and cobalt. However, the significant leaching of nearly all the iron from the solids results in a high acid consumption and requires a high initial acid addition. Nickel laterite acid leaching technologies are underpinned by the use of sulfuric acid and this is the focus of the processes described below. Other emerging atmospheric leaching technologies that employ hydrochloric acid and fungal or microbial metabolites (viz. organic acids) are reviewed by McDonald and Whittington (2008a).

3.2.1. High pressure acid leach (HPAL)

Until the startup of the three Australian HPAL plants (Cawse, Bulong and Murrin Murrin) in the late 1990s, there was just one

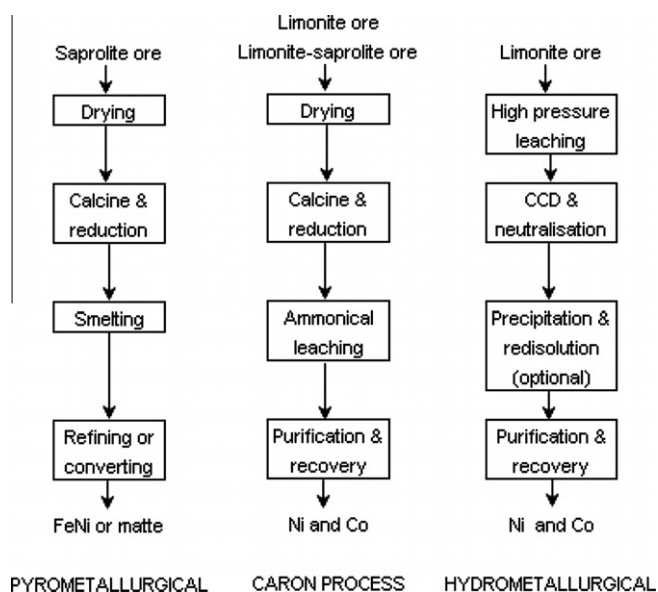


Fig. 1. Generalised laterite processing flowsheets.

commercial plant in the world doing acid pressure leaching of nickel laterites. Located at Moa Bay, Cuba, it was started up by the Freeport Sulfur company in 1959. In the HPAL process, the ore is beneficiated, where possible, to improve the nickel and cobalt concentration and improve the autoclave throughput. Conventional preconcentration techniques are generally unsuccessful for laterites ores since most of the nickel is dispersed in the iron oxides or clays rather than occurring as a discrete mineral (Whittington and Muir, 2000). The slurried ore is thickened prior to feeding to the autoclaves. Acid leaching occurs in titanium-lined autoclaves (Australian projects) or acid brick and lead-lined autoclaves (Moa Bay project) at a temperature of approximately 250 °C and a pressure of 4.1 MPa. The use of titanium is of particular importance to the Australian processing plants since this can resist attack from any chloride present in hypersaline process water. After digestion, the slurry is flashed to approximately 100 °C and the solids separated from the liquid in a counter-current decantation (CCD) thickener well. Once the nickel and cobalt have been leached into solution, there are a number of processing options available to recover them from the leach liquor. These include either direct treatment by solvent extraction and electrowinning (e.g. Bulong) or by indirect methods such as precipitation to produce an intermediate mixed nickel and cobalt product (e.g. sulfide, hydroxide or carbonate). These mixed intermediate products then require further processing to produce nickel and cobalt metal products (Kyle, 2010). The different processing options arise due to differences in the ore mineralogy and behaviour, production philosophy, perceived technical risk and economic considerations.

In the case of the HPAL/mixed sulfide intermediate flowsheet (e.g. Murrin Murrin, Moa Bay, Ambatovy (under construction)), the nickel and cobalt are precipitated as a mixed sulfide using hydrogen sulfide gas (produced on site), the process operating at 120 °C and 1000 kPa. The mixed sulfide precipitate is slurried in water and leached under oxygen pressure (1100 kPa) at 165 °C. Cobalt is removed by solvent extraction followed by hydrogen reduction and briquetting. The raffinate from cobalt extraction is treated by hydrogen reduction, briquetting and sintering to produce nickel briquettes. The major advantage of sulfide precipitation is its selectivity, with excellent rejection of all major impurities. The major disadvantage is that redissolution of the precipitate to recover nickel and cobalt as refined products requires oxidative pressure leaching. The mixed hydroxide intermediate process (e.g. Ravensthorpe, Ramu) is not as selective as sulfide precipitation, although the ammonia re-leach process is highly selective, with excellent rejection of iron, manganese and magnesium. The advantage of the process is the much simpler dissolution process using ammonia at low temperature and atmospheric pressure. The advantages of the mixed hydroxide intermediate process are outlined by Mackenzie et al. (2006).

One of the critical operating parameters of the HPAL process is the acid consumption. Magnesium, which is found in saprolite ores, increases the acid consumption and thus reduces the economic viability of the HPAL process for processing magnesium-rich saprolite ores. A major disadvantage of the HPAL process is that it requires sophisticated high-temperature/high-pressure autoclaves and associated equipment which are expensive, both to install and maintain, as well as expertise to operate properly and reach full capacity, resulting in higher capital and maintenance costs. Another disadvantage of the HPAL process is that it is limited to treating largely limonitic type ores because the presence of saprolite will cause a large, and often uneconomic, increase in sulfuric acid consumption due to the leaching of magnesium from saprolite as outlined above. Many laterite producers burn elemental sulfur to produce sulfuric acid while the acid plants consequently produce process steam as a by-product (Moskalyk and Alfantazi, 2003).

3.2.2. Atmospheric acid leach (AL)

Atmospheric leaching at lower temperature and in open vessels avoids the need for expensive HPAL autoclaves. McDonald and Whittington (2008b) have listed the relative strengths and weaknesses of AL versus HPAL and noted that a range of considerations must be examined when determining if AL is a viable processing option. Two key issues are the kinetics of nickel extraction and the ease with which the liquor can be subsequently processed. Various strategies have been examined to increase the recovery of nickel by AL or its selectivity over iron to decrease the consumption of acid. These include increasing temperature or leaching time, controlling redox potential, adding catalysts or pre-treatment (Watling et al., 2010) to change mineral phases (e.g. roasting). Sulfur dioxide or another suitable reducing agent can be added to the leach slurry to assist nickel and cobalt dissolution (Das et al., 2010; Watling et al., 2010). While not yet commercialised as a stand-alone process, AL has been used in the Ravensthorpe EPAL process.

3.2.3. Enhanced pressure acid leach (EPAL)

This process includes an additional leaching step for saprolite ores using residual acid from the HPAL step (plus added acid) at atmospheric pressure. In this two-stage leaching process, the limonite and saprolite ore components are respectively treated by HPAL and AL, with the AL step effectively consuming acid and partially neutralising strongly acidic liquors to leach further nickel from otherwise reject ore. In this way, the EPAL processes reduces acid consumption for laterite processing (Clark, 2007). However, the mineralogy and reactivity of the ore used for neutralisation is critical for high overall nickel extraction, with high magnesium saprolite ores generally performing better. This process formed the basis of BHP-Billiton's Ravensthorpe Nickel Operations in Western Australia which has now closed due to profitability concerns. This plant never reached full production capacity and faced technical problems which were not overcome during ramp up, and combined with a collapse in the price of nickel at the time, led to its premature closure. The overall performance of the EPAL process is influenced by the proportions of limonite and saprolite ore components treated in the process. In order to derive a first-pass estimate of the embodied energy and greenhouse gas footprints of this process for comparative purposes, the results for the HPAL and AL routes were combined in the same proportion as the HPAL/AL tonnage ratio reported for the Gladstone Nickel Project (Becker and Park, 2006), viz. 3.5:1 or 78% to HPAL and 22% to AL, while at the same time accounting for the reduced acid (and hence limestone) consumption in the process.

3.2.4. Heap leach

Heap leaching of low-grade laterites differs in principle from the established heap leaching of low grade sulfide ores although in practice both require irrigation with acid, good permeability and extensive leaching times over several months, at ambient temperatures (McDonald and Whittington, 2008b). The main concerns with nickel laterites are the high acid consumption, potential breakdown of the aggregated mineral structures and the poor selectivity of nickel over iron and magnesium. While there has been substantial refinement of process flowsheets for the downstream recovery of nickel from HPAL discharge slurries as outlined above, the same cannot be said for heap leach liquors. The pregnant leach solution (PLS) obtained from a nickel laterite heap leach exhibits some significant differences to a HPAL discharge slurry, namely, lower temperature, lower nickel concentrations and higher iron concentrations (Willis, 2007). The heap leach demonstration plant at Murrin Murrin recently commenced commercial operation (Readett and Fox, 2010). Due to a lack of data, only the

mixed hydroxide intermediate processing route was considered for heap leaching in this LCA study.

3.3. Pyrometallurgical/hydrometallurgical routes

The Caron process (e.g. Yabulu), developed in the 1920s, is a combined pyrometallurgical and hydrometallurgical process for lateritic ores. The nickel and cobalt are reduced to their metallic forms by heating the ore at a temperature above 700 °C in a reducing atmosphere, then the calcine is cooled to less than 200 °C by indirect water cooling to avoid oxidation of nickel and cobalt. An ammonia–ammonium carbonate solution then selectively leaches these materials. Boiling removes the ammonia and precipitates basic nickel carbonate which, upon calcination at 1200 °C, produces nickel oxide. The nickel oxide is converted to nickel metal in reduction furnaces under an atmosphere of hydrogen. The Caron process can be used for limonitic ores or a mixture of limonite and saprolite. Recovery of nickel and cobalt decreases with increasing amounts of saprolite since nickel and cobalt are locked in a silicate matrix and are difficult to reduce at 700 °C. However, the process can tolerate higher amounts of magnesium than the HPAL process. The Caron process suffers from several disadvantages:

- the front-end of the process is pyrometallurgical involving drying, calcining and reduction which are energy intensive;
- the back-end of the process is hydrometallurgical requiring various reagents;
- the nickel and cobalt recoveries are lower than for the pyrometallurgical processes or the HPAL process.

4. Sustainability and life cycle assessment

Sustainability concerns have focussed attention on the supply chains and life cycles of metal production and product manufacture, which has highlighted the need to take a life cycle approach in assessing the true environmental impact of primary metal production. This approach takes into account material and energy inputs occurring external or upstream of the metal production stage – so-called indirect inputs. The mining, mineral processing and metal production sector, like other industrial sectors, has come under increased pressure to reduce the amounts of energy it consumes and greenhouse gases it emits. This has led to the application of LCA methodology to the production life cycles of most metals (Norgate et al., 2007a).

There is ongoing debate as to the most appropriate metrics to evaluate the sustainability of metal mining and production, with energy and GHG emissions being the focus of most LCA studies of primary metal production. These were also the main impacts considered in the LCA study described here. While exergy is increasingly being used as a sustainability indicator, it was beyond the scope of the study described in this paper. However, it would be a useful inclusion in any more wider sustainability assessment of nickel laterite processing. As this study, like most LCA studies, is for comparative purposes, the functional unit used should be the same for all laterite processing routes, with a functional unit of one tonne of nickel metal being used in this study, i.e. all results are expressed per tonne of nickel metal. For this reason, the embodied energy and GHG emissions were allocated to all valuable co-products, e.g. nickel, cobalt and iron (in ferronickel) on a mass basis. All processing routes were considered from laterite ore mining through to the production of nickel metal, except in the case of ferronickel, which is used in this form and not refined further into nickel metal. As the iron and nickel in the ferronickel product are not separated, and as the majority of ferronickel is used in stainless steel production (Stadelhofer et al., 2009), it is appropriate to as-

sign the environmental impacts of ferronickel production to nickel and iron weighted equally on a mass basis.

As the main purpose of the LCA study was to compare the energy and greenhouse gas performance of the various laterite processing routes themselves, rather than specific operations, the same fossil fuel-based (i.e. black coal) electricity was assumed for all processing routes considered. For similar reasons, no transport of any raw materials or nickel products were included in the study. Furthermore, in keeping with standard LCA methodology, the feed-stock energy of the sulfur burned in any on-site acid plant was also included in the embodied energy calculations. The LCA study was based on publicly reported data (e.g. literature, company websites, reports and presentations), which can often have limitations (Eckelman, 2010), including out-of-date information, aggregation of process steps and inappropriate treatment of co-products, supplemented with some data derived from process simulations by the authors. While the authors have endeavoured to address these data limitations in this study, the results are based on inventory data that in many instances could not be verified fully and therefore contain a degree of uncertainty, and as such, they should be regarded as indicative rather than definitive. The study was carried out in accordance with standardised LCA methodology and utilised both the SimaPro LCA software package and an Excel-based LCA model. In carrying out the study it was assumed that laterite ore contains 1.3% Ni, which is the mean world laterite ore grade according to Dalvi et al. (2004). While different laterite processing routes may have a certain range of grades for acceptable feed material, this was accounted for by examining the effect of feed ore grade on the results. It was also assumed that the black coal-based electricity generation efficiency was 35%.

5. Results

The embodied energy¹ and GHG results from the LCA study of nickel laterite processing routes are given in Table 1, along with typical nickel recoveries. The embodied energy and GHG results for the hydrometallurgical routes in Table 1 are the means for the various processing options (i.e. SX/EW, mixed sulfide or hydroxide intermediates) for which data were derived, and are compared with each other and some publicly reported LCA results in Figs. 2 and 3 respectively. The energy derived from burning sulfur in an on-site acid plant, together with the greenhouse gas emissions from subsequent acid neutralisation and the avoided emissions from using this energy in place of fossil fuel energy from coal and natural gas are shown in Fig. 4 based on reported limestone consumption for the HPAL process. However, it should be noted that the reduction in greenhouse gas emissions with an on-site acid plant shown in Fig. 4 would be offset by greenhouse gas emissions resulting from transporting sulfur to the plant, but as this is facility-specific it was excluded from the LCA as pointed out earlier, but to give an indicative value, transport of sulfur from Vancouver (Canada) by ship to Fremantle (Western Australia) and then to Murrin Murrin by road would generate approximately 2 t CO₂e/t Ni.

The heap leach and atmospheric leach processes do not require the use of a high pressure and temperature autoclave, resulting in lower energy consumptions compared to the HPAL and EPAL processes. While this may be expected to give lower greenhouse gas footprints for the former processes, this is offset by higher acid consumption for these processes (0.6 t H₂SO₄/t ore cf. 0.4 t H₂SO₄/t ore for the HPAL process) and its subsequent neutralisation with limestone. However, the effect of this offset is reduced with an on-site acid plant. The greenhouse gas emissions reported

¹ Embodied or life cycle-based impacts are the cumulative impacts over the 'cradle-to-gate' life cycle of the metal production process.

Table 1
LCA results for nickel laterite processing routes.

Process	Embodied energy (GJ/t Ni) ^a	GHG emissions (t CO ₂ e/t Ni)		Overall nickel recovery (%)
		With acid plant	Without acid plant	
<i>Hydrometallurgical</i>				
High pressure acid leach	272	22.7	27.3	92
Atmospheric acid leach	167	14.6	25.1	80
Enhanced pressure acid leach ^b	249	17.8	23.2	85
Heap leach	211	17.6	28.0	73
<i>Pyrometallurgical</i>				
Ferronickel	236	NA	22.4	95
<i>Pyro/hydrometallurgical</i>				
Caron process	565	NA	44.8	80

^a Includes sulfur feedstock energy of 84–126 GJ/t Ni (depending on hydrometallurgical processing route) with on-site acid plant – corresponds to approximately 35 t steam (high and low pressure) per tonne of nickel.

^b Based on 78% HPAL and 22% AL.

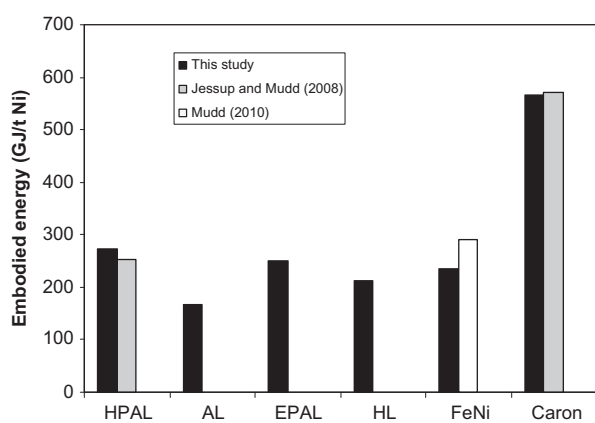


Fig. 2. Comparison of embodied energy results.

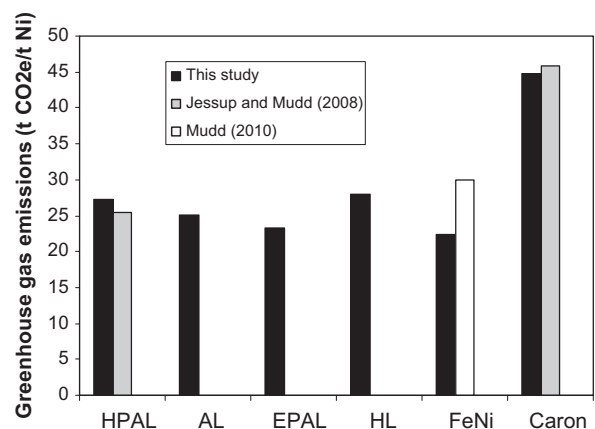


Fig. 3. Comparison of greenhouse gas emission results (without acid plant).

in Table 1 for the EPAL process are 17.8 t CO₂e/t Ni (with an acid plant) which compares favourably with a mean value of 17 t CO₂e/t Ni from the data reported by Clark (2007) and Becker (2009) for Ravensthorpe/Yabulu and the proposed Gladstone Nickel operations respectively.

6. Discussion

As mentioned earlier, there is often no real choice as to which processing route is used for a given laterite ore deposit – this is largely determined by the nature of the deposit, particularly the ore

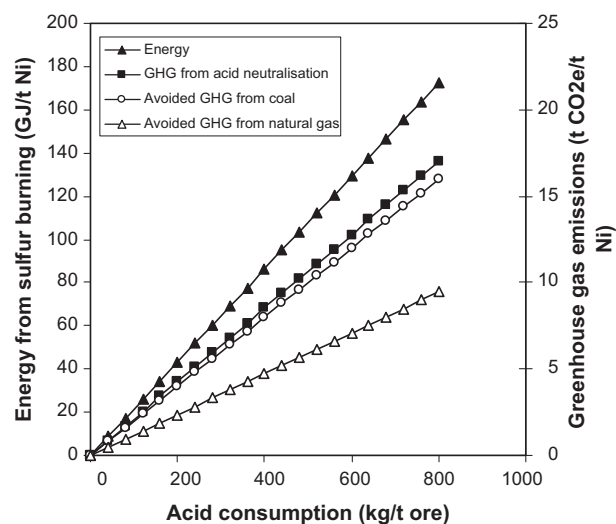


Fig. 4. Energy and greenhouse gas emissions from sulfur burning and acid neutralisation.

mineralogy and grade. Even when such choices are possible, economics is often the overriding factor. Throughput is an important issue in process selection, with typical throughputs of 60,000 tpa nickel for HPAL and AL plants and 30,000 tpa nickel for heap leach operations being reported (Wedderburn, 2009). The throughput of ferronickel plants can be up to 49,000 tpa nickel, with potential increase to 72,000 tpa nickel being suggested (Warner et al., 2006; Walker et al., 2009). Some important issues affecting the environmental sustainability of nickel laterite processing, along with some potential opportunities and technologies for improvement, are discussed below.

6.1. Greenhouse gas emissions

The energy and greenhouse gas footprints of the various nickel laterite processing routes in Table 1 and Figs. 2 and 3 range from 167 to 565 GJ/t Ni and 22.4 to 44.8 t CO₂e/t Ni (without acid plant) and 14.6 to 44.8 t CO₂e/t Ni (with acid plant) respectively. These results compare with values of 114 GJ/t Ni and 11.4 t CO₂e/t Ni from sulfide ores previously reported by the authors (Norgate et al., 2007a). Similar values for sulfide ores have been reported by Eckelman (2010) and Mudd (2010). It was pointed out earlier that the mining, mineral processing and metal production sector has come under increased pressure to reduce its energy and greenhouse gas footprints. Given the anticipated increase in nickel metal

production from laterite ores as mentioned earlier, these higher energy and greenhouse gas footprints for laterite ores will be critical sustainability issues affecting the future of the nickel laterite industry. To illustrate this point, calculations were made to show the likely increase in the price of nickel when produced from laterites compared to sulfides (based on the above value of 11.4 t CO₂e/t Ni from sulfides) with the imposition of a carbon tax, and the results of these calculations are shown in Fig. 5.

6.2. Effect of ore grade

The grades of metallic ores are falling globally as the higher grade reserves are exploited first and are progressively depleted. For example Mudd (2007) has shown that the average nickel ore grade in Australia fell from 3.8% in 1971 to 1.2% in 2004. Extracting nickel from these lower grade ores will increase the embodied energy (and associated GHG emissions) of nickel production due to the additional amount of material that must be processed to produce the same amount of nickel. By expressing the LCA results per tonne of laterite ore rather than per tonne of nickel metal as used in the figures and tables, the effects of ore grade on embodied energy and GHG emissions were estimated for the various nickel laterite processing routes and these are shown in Figs. 6 and 7 respectively.

6.3. Improving the environmental sustainability of nickel laterite processing

One obvious way of improving the environmental sustainability of nickel laterite processing is to utilise renewable energy sources where possible, either directly as a fuel and reductant (e.g. biochar in ferronickel smelting), or indirectly in electricity generation (e.g. for electrowinning or electric furnaces). However, there are a number of other potential opportunities for improving the environmental sustainability of laterite processing and these are discussed below, together with some possible technologies or approaches that might be utilised to achieve these improvements. The main focus of most of these approaches is improving the energy efficiency of the respective processes.

6.3.1. Pyrometallurgical processing

Wood char or biomass char (biochar) is considered renewable because the carbon cycle via wood (biomass) is very short (5–10 years) compared to fossil coal (approximately 100 million years). As the ferronickel smelting process consumes a substantial

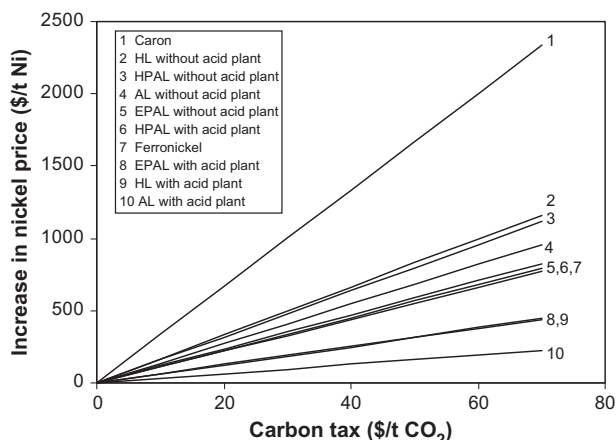


Fig. 5. Effect of carbon tax on increase in the price of nickel produced from laterites instead of sulfides.

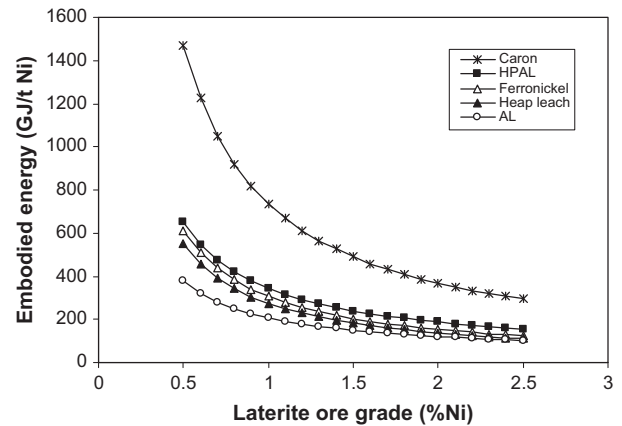


Fig. 6. Effect of laterite ore grade on embodied energy.

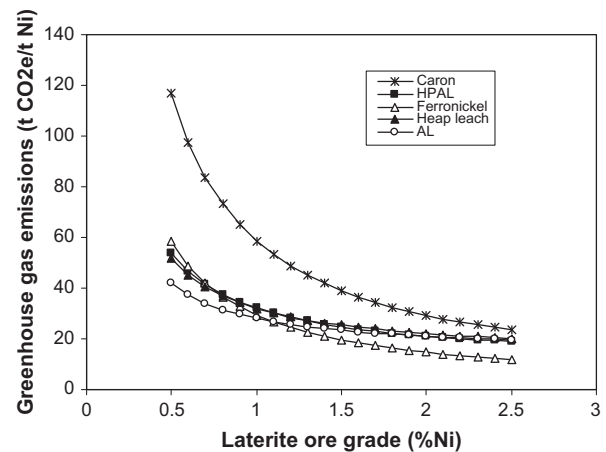


Fig. 7. Effect of laterite ore grade on greenhouse gas emissions (without acid plant).

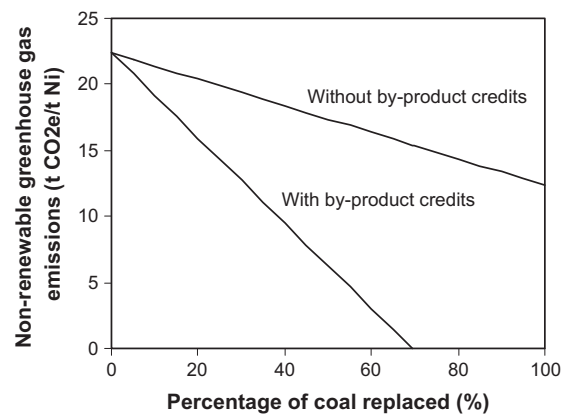


Fig. 8. Reduction in non-renewable greenhouse gas emissions using biochar in ferronickel smelting.

amount of coal (typically 3.9 t/t FeNi), the use of biochar in place of coal represents a significant opportunity to reduce the non-renewable (i.e. fossil fuel-based) greenhouse gas emissions from ferronickel smelting. Using the results² from a previous LCA of bio-

² Non-renewable greenhouse gas emissions from biochar production are 0.22 kg CO₂e/kg charcoal without by-product (electricity and bio-oil) credits, and - 5.98 kg CO₂e/kg charcoal with by-product credits of 6.20 kg CO₂e/kg charcoal included.

char production (Norgate and Langberg, 2009) together with the respective physical properties of coal and charcoal³, the reduction in non-renewable greenhouse gas emissions was calculated by assuming coal is replaced with biochar on an equivalent carbon basis, and the results are shown in Fig. 8. As shown in this figure, without by-product credits from biochar production the non-renewable greenhouse gas emissions from ferronickel smelting are reduced from 22.4 t CO₂e/t Ni (see Table 1) to 12.3 t CO₂e/t Ni for complete coal replacement with biochar. On the other hand, with the by-product credits included, the non-renewable greenhouse gas emissions are reduced to zero with approximately 70% replacement of coal with biochar. This occurs because of the non-renewable greenhouse gas credit that biochar has when the electricity and bio-oil by-products are accounted for.

One option for improving the energy efficiency of ferronickel production is the recovery of waste heat from the hot slag and gases leaving the electric furnace used for ferronickel smelting. Dry granulation of slag and subsequent heat recovery is receiving increased attention for iron blast furnace slags (Xie et al., 2007). Based on cooling slag from 1550 °C to 100 °C with 80% heat recovery, it has been estimated (Norgate et al., 2007b) that this corresponds to about 1.5 GJ/t slag. The amount of slag produced in ferronickel smelting is influenced by the Fe/Ni ratio in the ore, but for a typical ratio of 9 (Warner et al., 2006) about 14 tonnes of slag is produced per tonne of ferronickel. Therefore the potential amount of waste heat recoverable from the slag is in the order of 21 GJ/t ferronickel. This is roughly 10% of the ferronickel embodied energy reported in Table 1. The potential waste heat recoverable from the electric furnace offgases has not been estimated at this stage, but combined with the potential waste heat recovered from the slag, could significantly improve the energy efficiency and associated greenhouse gas emissions for ferronickel production.

Another option for improving the energy efficiency of ferronickel smelting is by the use of bath smelting technology (Norgate and Jahanshahi, 2004). A number of “direct smelting” processes using bath smelting technology have been developed in recent years to address some of the disadvantages suffered by blast furnaces. In these processes, smelting takes place in a single reactor where ore and coal are both charged into the same melt or bath (hence the name “bath smelting”). The processes utilise post combustion of the process offgases, the heat released being transferred back to the bath to compensate for the endothermic smelting reactions. These bath smelting processes potentially offer significant savings in the embodied energy for ferronickel production as the more direct use of thermal energy replaces electrical energy and its associated generation inefficiencies. The embodied energy and GHG emissions for ferronickel production by bath smelting have been estimated to be 146 GJ/t Ni and 13.7 t CO₂e/t Ni based on the results of Norgate and Jahanshahi (2004) corrected to a laterite ore grade of 1.3% Ni as used in this LCA study. These results are compared with those for the current process and also with slag waste heat recovery in Fig. 9.

6.3.2. Hydrometallurgical processing

For the hydrometallurgical leaching processes based on sulfuric acid outlined above, a significant amount of the life cycle-based greenhouse gas emissions result from neutralisation of the acid with lime or limestone as shown in Figs. 10 and 11 with and without an on-site acid plant respectively. In these cases there may be opportunities to reduce the greenhouse emissions from nickel laterite processing apart from those associated with improvements in energy efficiency. One possible option is non-acid leaching of the laterite ore, e.g. bio-leaching (McDonald and Whittington, 2008a;

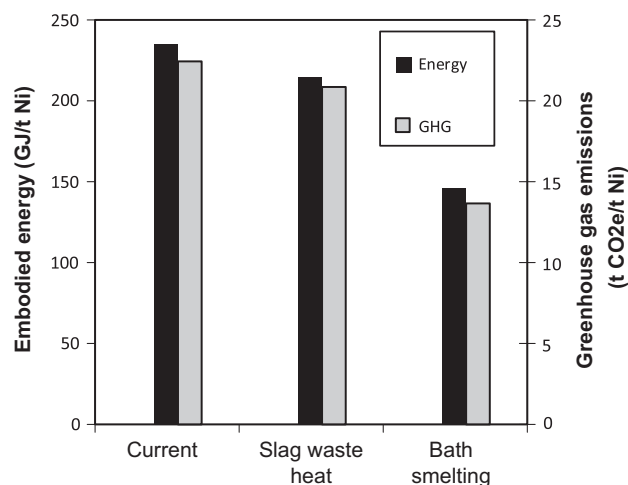


Fig. 9. Embodied energy and greenhouse gas emissions for ferronickel processing options.

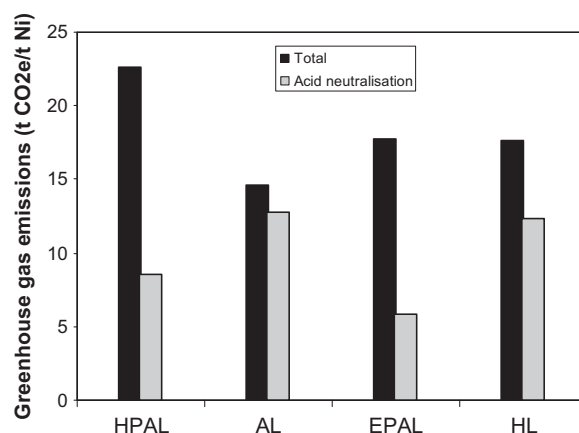


Fig. 10. Greenhouse gas emissions from hydrometallurgical processes (with acid plant).

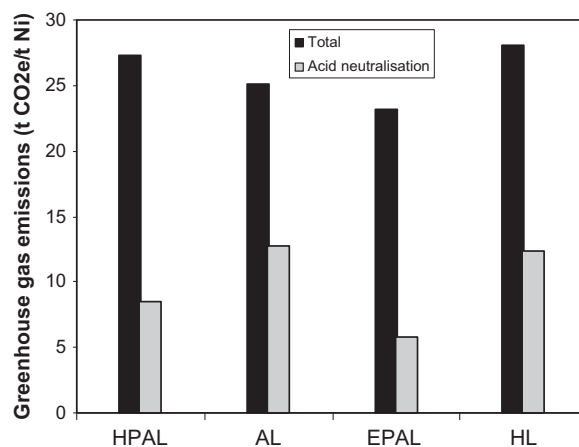


Fig. 11. Greenhouse gas emissions from hydrometallurgical processes (without acid plant).

Hallberg et al., 2010). Another possible option is the use of a neutralising reagent with a low greenhouse gas footprint, although this does not include caustic soda as the life cycle-based greenhouse gas emissions associated with its production exceed those from neutralisation with limestone.

³ Coal: 30 GJ/t, 81.3% C, 92.7 kg CO₂e/GJ; charcoal: 88.3% C.

The hydrometallurgical leaching processes can basically be divided into two stages – leaching of laterite ore and recovery of metal from the leach solution. Jansen (1999) carried out energy minimisation studies of the leaching stage of a HPAL plant and determined the optimum number of flash stages and the corresponding operating pressures and temperatures. Other efforts to improve the energy efficiency of the leaching stage include reducing the amount of material to be treated by pre-concentrating the ore, particularly for heap leaching⁴ (Anon, 2009). Improving the energy efficiency of the metal recovery stage will depend on the processing route used. In the case of electrowinning, it has been estimated by the authors that the power consumption observed in practice is more than double the theoretical value required for nickel electrowinning. Therefore it would appear that there is considerable scope for improving the energy efficiency of nickel production from laterite ores by focussing on nickel electrowinning. Current areas of electrowinning research of relevance here include alternative electrode materials to reduce the overpotential as well as improving mass transfer of nickel from solution to the cathode.

7. Conclusions

Significant growth in laterite production will be required in the future to balance the long-term supply of primary nickel metal as sulfide production falls off. This will see the development of complex laterite-based projects with higher capital, technical, environmental and operating costs risks. However, increasing focus on sustainability issues in the minerals and metal production industry means that the sustainability of these processes must be assessed at the earliest possible stage in their development. In this paper, life cycle assessment methodology has been used to assess the environmental sustainability of various processing routes for nickel laterite ores in terms of embodied energy and greenhouse gas emissions. While there is often no real choice as to which processing route is used for a given ore deposit – this is largely determined by the nature of the deposit, particularly the ore mineralogy and grade – such an assessment provides a useful comparison when there is some flexibility in processing route selection. Furthermore, the results of the assessment may be used to identify opportunities to improve the sustainability of the various processes and to examine how they might be affected under different future scenarios.

Based on the inventory data and associated assumptions used in the study, the results showed that the atmospheric leaching process had the lowest embodied energy, followed by the heap leach, ferronickel, enhanced pressure acid leach and high pressure acid leach processes. The Caron process had more than double the embodied energy of the other processes. However, it is emphasised that this study has focussed on the environmental sustainability of the respective process and that the relative economics (i.e. capital and operating costs) of the processes have not been considered. Utilising the waste heat generated from burning sulfur in an on-site acid plant to produce steam that would otherwise be generated using fossil fuels reduces the greenhouse gas emissions from the hydrometallurgical acid leaching processes. However, this reduction in greenhouse gas emissions would be offset by greenhouse gas emissions resulting from transporting sulfur to the plant, but being facility-specific, the latter was excluded from the LCA study.

The higher embodied energy and greenhouse gas emissions for nickel production from laterites compared to sulfides will be critical sustainability issues affecting the future of the nickel laterite industry. This situation will be exacerbated by any future decline

in laterite ore grades and also by the imposition of a price on carbon, either by carbon taxes or emissions trading schemes. Some potential opportunities to improve the energy and greenhouse gas footprints of nickel production from laterites have been identified in the paper. The use of biochar in place of coal in ferronickel smelting was shown to represent a significant opportunity to reduce the non-renewable greenhouse gas emissions from ferronickel smelting, with a 50% reduction in these emissions being indicated with full replacement of coal with biochar, even without any biochar by-product credits included. Waste heat recovery from slag and offgas were also identified as potential opportunities to improve the energy efficiency and hence the environmental sustainability of ferronickel smelting, with the former estimated to give a reduction of approximately 10% in embodied energy over current practice. The use of the emerging bath smelting technology for ferronickel production instead of the rotary kiln/electric furnace process was estimated to reduce the embodied energy by nearly 40%. As a significant amount of the life cycle-based greenhouse gas emissions from the hydrometallurgical acid leaching processes are generated by acid neutralisation with lime or limestone, there may be opportunities to reduce these emissions by utilising other neutralising agents or possibly by considering non-acid leaching systems, e.g. bio-leaching. Improving the energy efficiency of the electrowinning stage used to recover nickel metal from the leach liquor is another way in which the sustainability of the hydrometallurgical production of nickel from laterite ores could be improved. Preconcentration of the laterite ore to reduce the amount of material to be treated could also possibly improve the energy efficiency of both the pyrometallurgical and hydrometallurgical processing routes.

However, as the results from the LCA study described in this paper, are based on inventory data that in many instances could not be verified fully and therefore contain a degree of uncertainty, they should be regarded as indicative rather than definitive at this time. This is particularly so for the hydrometallurgical processes, where their varying levels of development mean that there is currently a general lack of detailed inventory data publicly available for these processes. Indeed, this ongoing development may mean that simple, single technology hydrometallurgical plants may not be built in the future, but hybrid flowsheets utilised instead.

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⁴ Preconcentration could also be applied to ferronickel smelting to reduce the amount of material to be heated up.

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