Climate change policy to foster pollution prevention and sustainable industrial practices – A case study of the global nickel industry

Roki Fukuzawa *

Centre for Sustainable Development, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom

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A B S T R A C T

The global metals industry is faced with multifaceted challenges as it is required to deal with declining ore grades, meet more stringent environmental regulations and be more energy efficient, all while remaining cost competitive. Using a case study of the nickel industry, the objectives of this research are to explore how climate change policies would influence the current industry operation and to evaluate their potential to achieve pollution prevention co-benefits. A multi-criteria decision analysis model was used to simulate industrial decision making and policy scenarios.

The results suggest that prices in the range of US $30–80 per tonne of carbon dioxide will likely promote efficiency improvements and energy recovery. However, they are not sufficient to drive innovations in processing methods or upstream pollution prevention. The co-benefits of climate change mitigation and pollution prevention cannot be readily realized under climate change policy alone. Increased coordination in policy making is necessary.

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1. Introduction

In light of the call for reducing emissions of carbon dioxide and other greenhouse gases, both the current industrial practices and environmental legislation need to be reformed so that the policy informs and reflects the co-benefits of climate change mitigation and environmental protection. A case study of the nickel industry was carried out to improve understanding of the interaction between decision making in industries and climate change policy development.

Nickel is an important metal in our modern society. It is used in stainless steel, alloys, electroplating and rechargeable batteries, all of which are integral to our economic growth and development (Eckelman, 2010). Among the broader sustainability debate on mining and metals production, nickel production is particularly energy intensive and therefore susceptible to emerging climate change policies which may lead to production curtailment and/or increased unit costs of production (Mudd, 2010).

Climate change is one of the many sustainability challenges faced by our society. Further challenges include other pollution to air, land and water, resources shortage and economic development. From a policy perspective, it is important to balance multiple and often competing needs in an integrated manner. It would require some levels of trade-off in order to maximize the overall effectiveness but also to ensure that one policy does not undermine other policy objectives.

The objectives of this study are to evaluate how developments in climate change policy could affect the nickel industry's current operation and how integrated approach to policy-making could provide clear sustainability signals to the industry. The study also aims to provide a reality check for the currently proposed carbon prices.

2. Mining and sustainability: an overview

Mining, defined as the extraction of finite resources from the earth, is intrinsically unsustainable. Historically, mining and metals processing have been associated with pollutions to air, water and land. They are also recognized as energy intensive activities which contribute to climate change.

What drives mining and metals production is the strong demand in our modern society as metal products are integral to economic development (e.g. infrastructure, transportation, etc.). Demand management is certainly a priority for sustainable development. When evaluating the entire value chain of metals, demand reduction can be more effective than technology improvements in mitigating climate change risks as demonstrated in a case study of copper in the United States (Giurco and Petrie, 2007). However, tackling the sustainability issue from the demand side would likely involve significant modifications to our current economic model and social/political structure. The current economic model is more material-based than service-based. Demand reduction such as
purchasing fewer goods may be perceived as suppressing economic growth. This is never favoured by politicians as they try to win votes from the public who thrives to improve the standards of living which is often linked to purchasing power.

Nearly 70% of nickel is used for stainless steel fabrication. The demand for nickel is mainly driven by the rising production of stainless steel in emerging economies (Eckelman, 2010). For example, China is currently the largest consumer of nickel. At a household level, there are strong demands for stainless steel appliances, cookware and other goods as symbols of improved lifestyle. At a societal level, there are needs for infrastructure development to support progressive urbanization. This trend seems to be followed by other developing countries. Such development model should be questioned from a sustainability perspective. However, this is beyond the scope of this study.

On the supply side, although metal resources are finite, metals generally do not degrade and can be recycled almost infinitely. Therefore, from a resource perspective, recycling of metals can be part of the solution towards sustainable development, not to mention other environmental benefits. Some metals are recycled more than others. For example, the world steel industry has taken enormous strides in maximizing recycling rates over the past 50 years (Yellishetty et al., 2011). However, for certain metals such as nickel while the demand is growing, recycling is currently not the most economical way of supplying the demand (Mudd, 2010). A number of factors affect the general economy of metal recycling including availability of virgin resources, costs of mining and processing of virgin ores, ore grade, availability and prices of metal scraps as well as metallurgical characteristics (Yellishetty et al., 2011). In the case of nickel, according to Mudd (2010), the currently known economic resources should provide for a century of production at an annual growth rate of 4.5% (equivalent to the average growth rate from 1950 to 2009). There are also metallurgical challenges to economically extract nickel from scraps (Yellishetty et al., 2011). Furthermore, the current high prices of nickel justify the costs of production from virgin resources.

While demand reduction and recycling are part of long term goals, it is important to examine the current practice and make improvements in more immediate term. For the metals industry, improvements in operational efficiency, environmental and social performances have been observed, but they are rather gradual than drastic. Some of the barriers impeding the transition can be unveiled from this case study of nickel.

The nickel industry has always faced environmental challenges such as air emissions, toxic effluents and wastes. For example, airborne nickel and some nickel compounds (e.g. nickel subsulfide, nickel oxides) are recognized as human carcinogens. Consequently, emissions reduction has been a key issue for the industry to address.

Climate change risks associated with anthropogenic greenhouse gas (GHG) emissions add a new dimension to the environmental challenges faced by the nickel industry. Noragte et al. (2007) compared multiple commonly used metals and their processing routes and identified that nickel processing has higher gross energy requirement and carbon dioxide (CO2) equivalent emissions than processing of other commonly used non-ferrous metals such as copper, lead and zinc (Noragte et al., 2007). Nickel processing was also found to be one of the least energy efficient processes among these metals at it had the highest ratio of actual versus theoretical energy requirements (Noragte and Jahanshahi, 2010). The smelting and refining (production) stages account for a larger portion than the mining and transportation stages (Eckelman, 2010). These factors make the nickel industry vulnerable to GHG reduction policies and carbon prices. Based on Noragte and Jahanshahi’s (in press) assessment, the increase in production cost can be as high as US $700 per tonne of nickel for the commonly used laterite processes at a carbon tax of US $70 per tonne of CO2.

There are two types of nickel ores: sulfide and laterite. The focus of this analysis is on nickel laterite ore processing. While about 60% of the world’s land-based nickel resources are contained in laterites, they currently account for only about 40% of world’s nickel production. Production from sulfide ores has been favoured historically because sulfides generally have higher ore grade and it is easier and less costly to extract nickel from sulfide ores. However, major sulfide resources have been exploited and there have been limited new sulfide discoveries of significance (Mudd, 2010; Noragte and Jahanshahi, 2010). The strong demand coupled with declining sulfide ores makes nickel laterite a bigger portion of the future supply. Looking at the new projects in the pipeline, laterite is expected to add more than 500 kilo-tonnes of capacity in the next decade while sulfide would only add 20 kilo-tonnes (Cartman, 2010).

However, the production processes for laterites are more energy intensive than sulfides, which adds complexity to the sustainability issue. This is due to two main reasons (Mudd, 2010; Noragte and Jahanshahi, in press):

- Laterite ores cannot be easily upgraded resulting in greater quantities of materials to be processed.
- Sulfur in sulfide ores acts as a fuel source which is not present in laterites.

With this trend, Mudd (2010) argued that not only resource availability, but also environmental and energy constraints would limit future nickel production particularly from laterite, and hence become the real basis for the concept of “peak nickel” to emerge.

The focus of this study is on the synergy between pollution prevention and climate change mitigation. It is often less energy intensive to prevent pollution than to treat it afterwards: as such the synergy presents an opportunity for climate change policy to promote cleaner industrial practices. The study aims to evaluate technically viable options using a multi-criteria approach with considerations for legislative barriers, all of which are limited in the current literature.

3. Methodology

An environmental input–output analysis on the nickel laterite processing industry was carried out in order to identify the significant contributors to CO2 emissions. CO2 reduction opportunities were identified for these significant contributors. These opportunities were compared to the current practices (i.e. business as usual) using a multi-criteria decision analysis (MCDA) model with carbon prices incorporated as variables to influence decision making.

3.1. Environmental input–output analysis

The production methods for nickel, like other non-ferrous metals, can generally be grouped into pyrometallurgical and hydrometallurgical routes. Currently, nickel laterite ores are being processed by one of the following methods:

- Rotary Kiln Electric Furnace (RKEF): accounting for about 75% of nickel production from laterite ores; the main product is ferro-nickel (FeNi).
- High Pressure Acid Leach (HPAL): accounting for about 16% of nickel production from laterite ores; the main products are Class I nickel (>99% Ni) and some cobalt (Co).
- Caron process: the first commercial process but is becoming obsolete.
The dominant RKEF and the HPAL processes are the focus of the analysis as they account for more than 90% of nickel production from laterite ores. Using the data from literature as well as process design information, an overall picture of the 2008 nickel production was generated (see supplementary information). With this information, the energy intensity and CO₂ emissions per tonne of product can be estimated. The data sources include:

- 2008 production data and ore grade (Mudd, 2010).
- Facility-level design and/or operating data.
  - Journal of Metal (JOM) world nickel laterite smelter survey (Warner et al., 2006).
  - Industry review (Chemlink Pty Ltd., 1997).
  - Hatch’s in-house data (Rogers, 2011).
- CO₂ emission factors.
  - Emission factors for fossil fuel combustion (USEPA, 2004).
- Life Cycle Assessment (LCA) data in literature (Eckelman, 2010; Norgate and Jahanshahi, in press; Roche, 2005; Rodd et al., 2010; Rogers, 2011; Vale, 2010). The focus was on the significant CO₂ contributors identified in the mass and energy input–output analysis.

For RKEF facilities, facility-level information such as fossil fuel consumption, types of fuel used and furnace power rating was used wherever possible. Fourteen smelters located in ten countries were included in the analysis (see supplementary information). It should be noted that CO₂ emissions are sensitive to the types of fuel used for ore processing and for electricity supply in these smelters. The direct CO₂ emissions (related to fossil fuel burning) are calculated using the emission factors of the fossil fuels and the annual consumption of the facilities. The indirect CO₂ emissions (related to electricity consumption) are based on where the facilities are located. Some countries such as Brazil have high percentage of renewable electricity where the grid CO₂ emission factors are low, while most other countries have low percentage of renewables. The indirect CO₂ emissions are calculated using the national average electricity grid emission factor and the electricity consumption of the facilities. The main drawback of the bottom-up approach is that the estimates may miss miscellaneous smaller energy users. As a check, the results were benchmarked against the Life Cycle Assessment (LCA) data in literature (Eckelman, 2010; Norgate and Jahanshahi, in press) subtracting the mining and transportation stages.

For HPAL facilities, the same level of facility data was not available as there are only limited facilities operating. Published design data from the Western Australian facilities and mass balances were used to estimate reagent, fossil fuel and electricity requirements. The results were also benchmarked against LCA data in literature (Eckelman, 2010; Norgate and Jahanshahi, in press) as well as reported data in environmental impact assessment reports (Roche, 2005). The electricity grid CO₂ emission factors were the averages of Cuba, Australia and Philippines, where HPAL facilities are located.

Further details on the assumptions used are included in the supplementary information.

### 3.2. Opportunity Identification

The decision making process in executing a greenfield nickel project can generally be categorized into the following stages using commonly adopted project implementation guidelines.

- **Stage 1:** Project Definition.
- **Stage 2:** Process Selection & Evaluation.
- **Stage 3:** Detailed Design & Implementation.
- **Stage 4:** Operations.

As a project moves along these stages, it becomes more locked in, and the possibility for implementing changes or improvements decreases. This is also true for facilities in operation. For example, it is unlikely for an operating facility to risk production in order to overhaul the core process or make significant modifications to processing technologies. Therefore, Stages 3 and 4 represent the opportunity window for existing facilities, with the exception of modifying auxiliary systems which would not impact the core process (e.g. electricity supply). Although more significant improvements are expected from greenfield projects, existing facilities are not exempted from the requirements to implement changes in order to meet more and more stringent regulatory demands.

CO₂ reduction opportunities along with their costs and effectiveness were identified through the review of literature as well as industry reports (Department of Energy and Climate Change, 2010; IEA, 2009a; King, 2005; Norgate and Jahanshahi, in press; Roche, 2005; Rodd et al., 2010; Rogers, 2011; Vale, 2010). The focus was on the significant CO₂ contributors identified in the mass and energy input–output analysis.

### 3.3. Multi-criteria Decision Model

There are many multi-criteria decision analysis (MCDA) tools to assist decision making under multifaceted constraints. In contrast to cost benefit analysis where all parameters need to be converted to monetary values, MCDA can be used when decision criteria and/or performance of alternatives cannot be easily quantified in monetary values (e.g. environmental benefits). Among these tools, the Analytical Hierarchy Process (AHP) was chosen for this study. AHP is a quantitative method that dissects an issue into a hierarchy of sub-issues so that each can be analyzed independently. Both quantitative and qualitative data can be used to evaluate the relative importance of criteria and/or the relative performance of alternatives. It then generates a ranking of options in a systematic and transparent manner.

Similar to many decision-making processes, an objective is first established and the decision criteria are developed to achieve the objective. The criteria can be divided into sub-criteria and weighted according to their relative influence. Options are assessed through pair-wise comparison of performances against each sub-criterion independently to generate a score. This score is then combined with the weight of the sub-criterion and summed up across all the criteria to generate an overall score for the option; this determines the ranking of the option.

Unlike most of the other quantitative MCDA tools, AHP does not require the use of specialty software and can be completed in an economical and timely manner, which makes it suitable as a screening level tool. For this type of high level decision making where options are not fully defined and the information is limited, a relative comparison of options against a set of criteria may be the best judgment that can be made. Provided that comparison judgment is made with robust reasoning, it would lead to a logical outcome because one advantage of AHP is its ability to detect inconsistent judgments. However, there is some degree of subjectivity associated with weighting the criteria and qualitative comparison of options. Another limitation of AHP lies in the fact that the selection of stakeholders involved in the exercise would significantly influence the decision process and the outcomes. In this study, a few technical specialists in the industry were consulted to simulate industrial decision making. In practice, the decision makers should consult as many affected stakeholders as possible and carry out the analysis in a transparent manner. The criteria weighting should be adjusted to meet the specific project requirements. The comparison should be made based on the most robust information available at the time.

The generic AHP model used is shown in Fig. 3-1.
As shown in Fig. 3-1, there are technological, financial, environmental and institutional criteria to be considered in all stages of decision making. It should be noted that environmental criteria here indicate beyond-compliance performance since it is assumed that any new projects or existing facilities are in compliance with the minimum regulatory requirements. Social criteria are not included in the scope of this study because the analysis focuses on processing methods and technology selection, and social impacts would not be differentiating criteria at those stages of decision making.

The decision criteria were developed based on project experience and consultation with industry specialists. The weightings of the four criteria are developed through a pair-wise comparison of relative importance. Representing the current industry mentality, financial criteria are of the most significance in decision making, followed by technological, institutional and (beyond-compliance) environmental criteria.

3.4. Policy scenario modelling

The business-as-usual (BAU) scenario is established by comparing the current practices with alternative processing methods and/or CO2 reduction options in the AHP model with no restriction on CO2 emissions.

Using the decision model, a market-based climate change policy was assessed. The instrument can be either carbon tax or emission trading scheme (ETS). From a macro-economic perspective, they are similar in the sense that a price is put on CO2, although the implementation of these two instruments is different. In the case of carbon tax, the price of CO2 is determined but the achievable emission reduction is unknown to policy makers. For an ETS, the expected emission reduction is known or determined by policy makers and the price of carbon is uncertain depending on the number of permits distributed and how they are distributed. In addition, an ETS would offer financial incentives for further reduction as the unused permits can be sold, but carbon tax would not. For the purpose of this analysis which concerns how a price on CO2 would affect microeconomic industrial decision making, the policy is simply modelled as a set of low, medium and high CO2 prices. The price on CO2 is incorporated into the financial criteria as an increase in operating costs in proportion to the CO2 emissions per tonne of nickel produced in each option.

The scenarios are:

- Low CO2 price: $30/tonne.
- Medium CO2 price: $50/tonne.
- High CO2 price: $80/tonne.

The currency for all costs used throughout this paper is US dollar (USD). The price range is based on a survey of eleven published reports on recommended carbon prices carried out by the Climate Change Risk Mitigation (CCRM) project team (CCRM, n.d) at Cambridge University. Both direct and electricity-related indirect CO2 emissions are considered applicable to the policy.

4. Results and discussion

4.1. The current practice

The energy and CO2 intensities associated with processing one tonne of nickel products through RKEF and HPAL are summarized in Table 4-1.

When benchmarking the above results against other studies, it should be noted that ore grade is a significant influencing factor. In general, a decrease in ore grade would imply an increase in energy requirements and CO2 emissions (Norgate and Jahanshahi, 2010, in press; Eckelman, 2010). Fig. 4-1 confirms this finding by benchmarking this study against two relevant studies as a function of average ore grade used. In Norgate and Jahanshahi’s study (in press), an average of 1.3% nickel was used for all laterite processes. In Eckelman’s (2010) study, facility-level data was used but the average ore grade for RKEF and HPAL was not explicitly reported. Based on Fig. 4a of his paper, an average for all laterites can be estimated to be around 1.9%. In addition, Norgate and Jahanshahi’s

<table>
<thead>
<tr>
<th>Process</th>
<th>Main product(s)</th>
<th>Average ore grade</th>
<th>Energy intensity (GJ/t of product)</th>
<th>CO2 intensity (t/t of product)</th>
<th>CO2 intensity (t/t of Ni)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RKEF</td>
<td>FeNi (15–45% Ni)</td>
<td>1.8%</td>
<td>128</td>
<td>14</td>
<td>44</td>
</tr>
<tr>
<td>HPAL</td>
<td>Class I Nickel (&gt;99% Ni) + Cobalt</td>
<td>1.4%</td>
<td>180</td>
<td>20</td>
<td>21</td>
</tr>
</tbody>
</table>
The CO2 intensity for RKEF calculated in this study is 63% of the value in Norgate and Jahanshahi’s study (in press). The difference can be attributed to the different average ore grade used (1.8% vs. 1.3%) as well as mining and transportation.

The CO2 intensity for HPAL calculated in this study is 87% of the value in Norgate and Jahanshahi’s study (in press). This difference can be attributed mainly to mining and transportation, and to a lesser extent, ore grade difference (1.4% vs. 1.3%).

The relative contribution from various processing steps to energy and CO2 intensities for RKEF and HPAL are summarized in Fig. 4-2. In RKEF, the most significant contributors are direct fossil fuel burning in calcine reduction and electricity usage in electric furnace smelting. These results are based on the current energy mix used in RKEF smelters globally. Coal accounts for more than half of the energy inputs to drying and calcine reduction, followed by fuel oil and natural gas. For HPAL, it is less clear-cut where and what type of energy is used at various processing steps, but the most significant contributors to CO2 emissions are electricity usage throughout the process and acid neutralization with limestone. In this case, the results are more sensitive to the grid energy mix of the countries where HPAL facilities are located.

4.2. Carbon dioxide reduction opportunities

The CO2 reduction opportunities identified for each stage of decision making are summarized in Fig. 4-3. More details on each opportunity including costs, CO2 reduction potentials, co-benefits of pollution prevention and other implications are presented in Table 4-2. All quantitative measures were normalized based on one tonne of nickel produced. The cost implication of each option is represented by the annualized incremental cost compared to the baseline. This annualized cost is the sum of the best estimate operating cost and capital cost annualized over a period of 20 years using a discount rate of 7%. It should be noted that the values are indicative for comparison purposes, as commercial experience with these options in the nickel laterite industry is very limited.

4.2.1. Process selection

For process selection, pyrometallurgical and hydrometallurgical routes were investigated separately as they are designed to treat different fractions of laterite ores. In general, saprolite fractions are suitable for pyrometallurgical processing while limonite fractions are suitable for hydrometallurgical processing.

Within the pyrometallurgical route, RKEF is the proven process which has been dominant since the 1970s. This process often involves batch transfer of hot calcine from the rotary kiln to the electric furnace, which generates significant fugitive emissions (containing nickel and other air toxics). An innovative way of integrating similar unit operations in a continuous manner was developed by Noranda/Falconbridge and named the Nickel Smelting Technology (NST). It is currently being commercialized at the Koniambo project in New Caledonia. The benefits of NST are improved metal recovery, reduced fugitive emissions and lower cost of production due to energy and fuel savings. The energy savings come from the use of a direct current electric furnace and the counter-current flow of furnace off-gas to assist in the reduction and drying of the incoming ore. The continuous process also eliminates batch transfer of materials and the associated fugitive emissions. All process related emissions are captured in a single gas-cleaning system, eliminating the need for a dedicated system for each unit operation (i.e. additional energy consumption). The Koniambo project is scheduled for commissioning in 2012, so the commercial success of this process is yet to be proven. The most recent cost estimate of the project is $3.85 billion (Xstrata Nickel, 2011), making it similar to the high estimates of the RKEF process.

Within the hydrometallurgical route, HPAL is the current process with four facilities in operation as of 2008. Although the limonite fraction is more abundant than the saprolite fraction (Dalvi et al., 2004), hydrometallurgical processes for nickel laterite has more technical risks than RKEF as observed in the Australian experiences with Murrin Murrin, Bulong, Cawse and Raventhorpe. None of them have achieved their design capacity and the project costs were significantly over-budget (Wedderburn, 2010).
Recently, the Coral Bay project in Philippines has demonstrated some promising signs. Nevertheless, the struggles with HPAL have led to the development of new processes such as Atmospheric Leaching (AL), Enhanced Pressure Acid Leaching (EPAL) and Heap Leaching (HL). Both AL and EPAL can reduce CO2 emissions; the former by eliminating the use of high pressure vessels (i.e. autoclaves) and the latter by better usage of residual acid to reduce the neutralization requirement. HL, however, does not seem to yield a net reduction of CO2 emissions although it is mechanically much simpler than the other process methods. This may be a result of high acid consumption and subsequent neutralization requirement.

### 4.2.2. Incremental improvements

Incremental improvement opportunities were only identified for pyrometallurgical processes using RKEF as the baseline because insufficient information is available on operating HPAL plants to carry out a similar analysis.

#### 4.2.2.1. The “low hanging fruits”.

The commonly recognized opportunities are the so called “low hanging fruits” such as process optimization and equipment efficiency improvements. There are many alternatives depending on the existing operating practices and equipment used. The CO2 reduction and costs would also vary accordingly. For this analysis, information from Vale’s Carbon Initiative at its PT Inco nickel laterite smelter was used to represent a realistic estimate (Vale, 2010). Although no cost information was available, it was assumed that these measures are cost neutral meaning that the capital investment can be quickly recovered through annual savings in operating costs. These measures are consistent with the pollution prevention strategy to improve process efficiency, but the actual co-benefits of emissions prevention have to be assessed on a case-by-case basis.

#### 4.2.2.2. Off-gas heat recovery.

The off-gas from the electric furnace contains considerable amounts of energy, which can be integrated into the process in different ways resulting in a range of improvement potentials and costs. For this analysis, an option involving recycling the furnace off-gas to the kiln was used.

#### 4.2.2.3. Slag heat recovery.

About 80% of the total energy inputs into the electric furnace exits as thermal energy in the slag (Rodd et al., 2010). Currently, slag from RKEF smelters is either allowed to cool in large slag pits or granulated using water while the thermal energy is wasted. Dry granulation as implemented at Fukuyama Steel Works in Japan was reported to have captured 80% of the slag energy to produce steam (Rodd et al., 2010). However, it has not been commercially used in the nickel laterite industry. The challenge seems to lie in the integration of the recovered energy back into the operation due to the intermittent nature of slag tapping. In addition, low fuel costs have not been able to justify more in-depth investigation of this option. Among a number of configurations to recover and integrate the energy into the process, the most cost effective option identified by Rodd et al.’s study (2010) was used for the analysis. This involves generating superheated steam for power generation.

#### 4.2.2.4. Bio-char.

The calcine reduction stage of the RKEF process is the most significant contributor to CO2 emissions. The carbon in coal is used for reduction, so substitution with a carbon-free reductant is not technically feasible. However, bio-char produced through pyrolysis of biomass may potentially be able to substitute for coal in this operation. Pyrolysis is the thermal decomposition of biomass in the absence of oxygen, usually carried out in a kiln. CO2 will still be generated using bio-char, but it is from renewable sources rather than non-renewable sources as the carbon cycle in biomass is significantly shorter than that in fossil fuels.

According to Norgate and Jahanshahi (in press), about 50% reduction in non-renewable CO2 emissions with full replacement of coal is possible. This is considered optimistic as bio-char has not been used in the nickel laterite industry and its technical risks are not...
4.2.3. Decarbonizing electricity supply

In both RKEF and HPAL, electricity related CO₂ emissions account for about 50% of the total. To reduce or eliminate these emissions, renewable electricity can be either purchased through the grid or developed onsite. Only base-load renewable energy options which are capable of sustaining the demand of metallurgical operations are considered here. Intermittent energy sources such as solar and wind are not viable without energy storage or backup generators. Also, decarbonizing electricity usage can be considered as nitrogen oxides, sulfur dioxide, dust and mercury.

4.3. Decision analysis and scenario modelling

4.3.1. Process selection

4.3.1.1. Pyrometallurgy. A range of CO₂ prices from $30 to $80 per tonne were applied when comparing two pyrometallurgical processes, namely RKEF and NST. The results show that RKEF is preferred to NST under all these price scenarios as well as the BAU scenario (no climate change policy). This suggests that the currently recommended prices of CO₂ would not influence the choice between RKEF and NST. The CO₂ savings as well as the co-benefits of pollution prevention are discounted by mainly in-creased cost of production and technological risks. The annualized co-benefits have to be assessed on a case-by-case basis.

4.3.1.2. Hydrometallurgy. The CO₂ reductions for hydro-electricity and Carbon Capture and Storage (CCS) are based on complete offsetting electricity associated CO₂ emissions. Hydro-electricity and combined heat and power (CHP) would have some co-benefits of air pollution prevention/reduction compared to coal-based electricity, which emits contaminants such as nitrogen oxides, sulfur dioxide, dust and mercury.

4.4. Description of opportunities.

<table>
<thead>
<tr>
<th>Decision stage</th>
<th>Current practice</th>
<th>Opportunities</th>
<th>BAU annualized incremental costs ($/t of Ni)</th>
<th>CO₂ reduction potential</th>
<th>Co-benefits</th>
<th>Other implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 2</td>
<td>Pyrometallurgy</td>
<td>rotary kiln</td>
<td>Falconbridge Nickel Smelting Technology (NST)</td>
<td>$1700 ($500 to $5600)</td>
<td>18%</td>
<td>Reduced fugitive air emissions due to continuous and integrated operation</td>
</tr>
<tr>
<td></td>
<td>Hydrometallurgy</td>
<td>atmospheric leaching (AL)</td>
<td>$2000 ($1700 to $12500)</td>
<td>11%</td>
<td>Better utilization of residual acid during the process to reduce the need for neutralization</td>
<td>Higher acid consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>enhanced pressure acid leaching (EPAL)</td>
<td>$1900 ($5100 to $7400)</td>
<td>21%</td>
<td></td>
<td>Limited commercial experience for nickel laterite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>heap leaching (HL)</td>
<td>$2800 ($10700 to $9400)</td>
<td>-4%</td>
<td></td>
<td>Higher acid consumption, Large plant footprint, Long leach cycle/low throughput</td>
</tr>
<tr>
<td>Stages 3 &amp; 4</td>
<td>Pyrometallurgy</td>
<td>process optimization</td>
<td>$0</td>
<td>0.05%</td>
<td>Consistent with the pollution prevention measure to improve process efficiency</td>
<td>Actual co-benefits have to be assessed on a case-by-case basis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>equipment efficiency improvements</td>
<td>$0</td>
<td>3%</td>
<td></td>
<td>Dust build-up and plugging of ductwork, Integration into the operation may be technically challenging due to intermittent slag tapping, Lack of commercial application in nickel laterite smelting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>off-gas energy recovery</td>
<td>$20 ($40)</td>
<td>18%</td>
<td>Potentially reduced volatile emissions from hot slag due to reduced slag temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>slag heat recovery</td>
<td>$200 ($50 to $340)</td>
<td>18%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>bio-char</td>
<td>$3500 ($200 to $7500)</td>
<td>50%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All Stages</td>
<td>Any process</td>
<td>coal-based electricity</td>
<td>combined heat and power (CHP)</td>
<td>$500 ($2400 to $3500)</td>
<td>25%</td>
<td>Reduced air emissions associated with reduced fossil fuel usage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>hydro-electricity</td>
<td>$500 ($2400 to $3500)</td>
<td>50%</td>
<td>Reduced air emissions associated with coal-fired power generation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>coal with Carbon Capture and Storage (CCS)</td>
<td>$2800 ($1300 to $6900)</td>
<td>50%</td>
<td></td>
</tr>
</tbody>
</table>

well understood. The costs are based on an order-of-magnitude estimate in comparison with the price of coal, because little published information is available.
is cheaper for companies to pay for the CO₂ emissions rather than to pursue a more costly and less proven processing method.

In order to change the preference in the scenario model, a CO₂ price of roughly $190/tonne is needed. With an international agreement on climate change mitigation still at stake, this price is quite unlikely to be seen in any jurisdiction in the near future. Factors that may reduce this price include the commercialization success of NST at Koniambo which would reduce the technological risks and innovations to reduce the costs of NST. Considering the uncertainties in costs, NST is similar to the high estimates of RKEF, which can be resulted from high energy or fuel costs. This coupled with a price on CO₂ can potentially make NST more attractive.

4.3.1.2. Hydrometallurgy. Similar results are observed for hydrometallurgical processes. A price on CO₂ at the currently recommended range will not influence decision making in process selection. HPAL remains as the preferred option, followed by EPAL, HL and AL. The technical risks associated with all the hydrometallurgical processes, especially for AL and HL, contribute to this finding. However, the main decision driver is still the relative costs as shown in Fig. 4-5. For AL and HL, the capital cost savings associated with eliminating the high pressure autoclaves are counterbalanced by increased operating costs on acid consumption and the resultant waste treatment. EPAL has better metal recovery due to the two-stage HPAL/AL circuits, but the costs are also higher.

In order to influence the choice of hydrometallurgical processes, a CO₂ price of about $370/tonne is necessary, in which case EPAL becomes the most favorable. This is even more unlikely in the near future. It should be noted that uncertainties associated with these costs are large, particularly for HL as the operating costs are strongly dependent on the ore grade and mineralogy.

4.3.2. Incremental improvements

At the design and operations stages, the influence of a price on CO₂ is shown in Fig. 4-6 with rank 1 being the most preferred option. Under the BAU scenario, pursuing incremental improvements such as process optimization and equipment efficiency improvements are preferable to the option of “do-nothing”. This trend is observed in the industry, and it is mainly driven by energy and operating cost savings. Off-gas heat recovery is also attractive, yet it has not been widely implemented in the nickel laterite industry. Some barriers include technical risks of coupling two unit operations which may decrease the equipment availability. Also, the furnace off-gas has a lot of dust which can build up in the recycling ductwork. This would affect equipment operation and maintenance requirements.

With a low CO₂ price of $30 per tonne, slag heat recovery becomes the most favorable option followed by off-gas heat recovery and the “low hanging fruits”. This trend continues through to the high CO₂ price scenario. Under all these scenarios, bio-char remains unattractive due to high technical uncertainty and high operating cost. The costs are quite comparable for all the other options including the baseline. The uncertainties are shown in the blue area in Fig. 4-7. Technical risks are likely the influencing factors for decision making while carbon prices may help change industry preference.

Taking into account the uncertainties in the price of bio-char relative to the price of coal, bio-char may be worth consideration in the medium to high price scenarios.

4.3.3. Decarbonizing electricity supply

Options for decarbonizing electricity were evaluated separately for pyrometallurgical (RKEF) and hydrometallurgical (HPAL) routes as the CO₂ intensities and costs of nickel production are different. The results are shown in Figs. 4-8 and 4-9.
For both cases, the BAU scenario suggests that coal-based electricity is the preferred option. With a low CO₂ price of $30/tonne, hydro-electricity becomes the most favorable. However, this would only be applicable when hydro resources are available at the location of the project. For RKEF, CHP becomes more attractive than baseline at the low CO₂ price, while for HPAL the change in preference occurs at the high CO₂ price. Under all scenarios, Coal + CCS remains too expensive and technically risky compared to the others.

5. Legislative barriers

It is important to note the legislative barriers considered in this analysis, although they may not be explicitly demonstrated in the results. These barriers are often missed in the analysis of policy implications on industrial practices.

The concept of pollution prevention has been promoted by regulators in many countries as a preferred approach to end-of-pipe solutions (Hossain et al., 2008; Miller et al., 2008; Wolnik and Fischer, 2006; Environment Canada, 2006). As demonstrated above, measures such as efficiency improvements have been sought after by the industry as they often lead to cost savings. However, economic, technological and legislative barriers, both individually and collectively, hinder the adoption of more upstream pollution prevention strategies in the mining industry. This is because the conventional end-of-pipe pollution abatement technologies are usually available “off the shelf”, which require less capital investment, less research and development (R&D) as well as less disruption to the operation compared to upstream modifications. In addition, the established abatement technologies, sometimes used as the reference in environmental regulations, are perceived by both the industry and the regulator to be the least risky way to be in compliance (Zarker and Kerr, 2008). This discourages innovation for more upstream and possibly more effective pollution prevention strategies.

In addition, climate change and air quality have been treated by separate legislative frameworks in national and international policies even though reducing GHG emissions often results in a reduction of air pollution, but the reverse is not always true (Intergovernmental Panel on Climate Change, 2007). If the nickel industry is required to continue to reduce air toxic emissions, end-of-pipe controls are certainly not discouraged by regulators, especially if they are referred to as the “best available techniques”. Existing facilities may be forced into implementing additional emission controls while further locking themselves into an energy-intensive practice. How would they respond to climate change policy then? Therefore, technology prescriptive and pollution control based environmental regulations can be a barrier for climate change mitigation. Furthermore, careful management of the interaction between environmental regulation and climate change mitigation can be challenging in reality because they are often dealt with at different platforms. Environmental regulations are managed at local/national platforms while climate change policy is managed at national/international platforms.

6. Conclusion and recommendations

The currently proposed carbon prices are insufficient to drive innovations towards less proven, more costly and potentially more environmentally sound processing methods. However, they may help justify some evaluation efforts. They will also reinforce the call for “picking the low hanging fruits”, promote energy recovery and renewable electricity supply. Combined with the current legislative barriers, the potential for climate change policy to promote pollution prevention is very small.

The following recommendations are formulated for policy makers dealing with climate change policy for industries.

- Recognize that innovation for sustainability may be promoted by other environmental drivers (e.g. NST was driven by reduced fugitive emissions). Therefore, increased integration of climate change policy and environmental regulations can be more effective than these policies implemented independently. This is also to ensure that environmental regulations do not overlook energy and CO₂ implications.
- Design climate change policy framework to be flexible to allow various ways of emission off-setting. This should be accompanied by a rigorous monitoring system to ensure a net reduction of CO₂. For example, decarbonizing electricity is an opportunity for the nickel industry to effectively contribute to climate change mitigation while generating pollution prevention co-benefits. Investing in renewable energy elsewhere (where the resources are available) to offset the energy use onsite should be considered.
- Further promote pollution prevention through other policy instruments such as incentives for process innovation and R&D as they could contribute to climate change mitigation.

The metallurgical industry is knowledge-intensive and has the potential to lead a more systemic change towards sustainable development. However, innovation requires high capital investments, long timeframes to commercialize and have high risks of failing in this particular industry (Imrie, 2006). Unsurprisingly, companies are more willing to pay for the environmental costs or make incremental improvements rather than to consider systemic changes. Also, uncertainties in technologies, costs, macro-economic climate and policy directions all prevent companies from taking strategic actions. These uncertainties should be further explored.

The AHP was used to demonstrate a multi-criteria approach to decision making in this study. It was appropriate given the level of
information available in the public domain as well as time and cost constraints. Other MCDA models should be considered in future studies, and the results should be benchmarked to see if they are sensitive to the selection of MCDA models.

Finally, this study focuses on ways to reduce the environmental impacts from the supply side of the metals value chain. It is important to keep in mind that these improvements have limited effectiveness without demand management. Strategies such as using less metal mass to provide similar services or making longer-lasting goods have not been explored as much in the metals industry as in energy and water industries (Giurco and Petrie, 2007). With declining ore grade and growing demand at a global level, there would be hardly any net reduction of environmental impacts even with cleaner production measures. Based on this study, climate change policies as they are designed now have limited effects on promoting cleaner production. Their impacts on demand management and wider transition of our social/economic model should be further investigated through a complete systems approach. This could be more effective than putting additional regulatory pressure on the supply side.

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Appendix A. Supplementary material

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References


