Environmental Sustainability Metrics for a Nickel Smelter

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Abstract

An environmental sustainability metrics is developed for a potential start-up nickel smelter. This is intended to enhance the sustainability of ferronickel production in terms of usage of resources and minimization of environmental burdens. The indicators include land use, laterite ore feed per ton of ferronickel product, fraction of laterite ore feed recovered by pelletizing, energy consumption, atmospheric acidification burden, global warming burden, and human health burden.

Additional mitigating measures for the negative externalities are also proposed.

Keywords: sustainability metrics, nickel smelting, environmental burdens, resources usage, ferronickel

Introduction

A new global ethic which has become widely accepted and endorsed is sustainable development. Sustainable development is "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs"

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as defined by the United Nations World Commission on Environment and Development. [1] The impact of industry on sustainability can be summarized in the "triple bottom line", covering the three components - environmental responsibility, economic return (wealth creation), and social development according to a Sustainable Development Metrics developed by the UK Institution of Chemical Engineers. [2]

Engineers being at the forefront of technology must take action and responsibility for a healthy and sustainable future. For an industry such as nickel smelting to guide its activities towards greater sustainability, specifically, in terms of environmental responsibility, concrete tools such as a sustainability metrics would be of great help to assess whether or not environmental enhancement is integrated into the production process.

Purpose of the Study

This paper aims to apply the tools of sustainability metrics in the production of ferronickel by surface mining and smelting. Specifically, it attempts to achieve the following:

1. to come up with a set of sustainable metrics to help guide a potential start-up nickel smelter;
2. to develop standards for internal benchmarking of operational efficiency and environmental performance at the start of its commercial operations;
3. to recommend monitoring frequency of the indicators; and,
4. to propose additional mitigating measures in the process flow.

Scope and Limitation

This report is limited to only one of the "triple bottom line" which is environmental responsibility, and, as such, will dwell only with the related environmental indicators.

Significance of the Study

This sustainability metrics would help guide a potential start up nickel smelter towards a more sustainable operation in terms of usage of resources and minimization of environmental burdens.

Review of Literature

Properties and Applications of Nickel

The chemical symbol for Nickel is Ni. It is a lustrous white, hard, ferromagnetic metal found in transition group VIII of the Periodic Table with an atomic number of 28. It has high ductility, good thermal conductivity, high strength, and fair electrical conductivity. Nickel can achieve several oxidation states including −1, 0, +1, +2, +3 and +4; however, the majority of nickel compounds are nickel +2 species. It has a specific gravity of 8.9 and a relatively high melting point of 1453°C. The electronic configuration of nickel is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^8 4s^2$. Nickel does not occur in nature as a pure metal but as a component of other minerals.

It has the ability to impart special features and desired physical properties to other metals. When alloyed with other elements, nickel imparts hardness, strength, toughness, corrosion resistance over a wide temperature range, and various other electrical, magnetic, and heat resistant properties.

At least 3,000 nickel alloys have been identified and these are widely used in the chemical industry, pipelines to carry seawater and in the highly stressed components for cars. In addition, nickel alloy steels are vital in modern weapons of war, and nickel-based super alloys which provide strength in the high-temperature jets that propel rockets into space. About 60% of the world nickel output is used in the manufacture of stainless steel according to Lenntech Nickel Data Sheet and a US EPA Report [3, 4].

Description of Nickel Ore

Nickel does not occur as a native metal. The economically important nickel ores can be divided into two types, sulfide and laterite (oxide or silicate). Of the estimated 58 x 10^6 metric tons world reserves of nickel, about 80% is in laterite ore bodies which is widely distributed throughout the tropics and only 20% in sulfide deposits as gathered from Unpublished Materials in the Extractive Metallurgy of Nickel [5]. Dalvi projected that growth in nickel production in the future is expected to come from the laterite ores of nickel. [6]

Laterite ores, occur in two main forms, oxides and silicates. In the oxide form, the nickel is dispersed through a limonite, a hydrated form of iron oxide, while the silicate form nickel partially replaces magnesium in the lattice of a hydrated magnesium silicate.

Nickel from laterite ores is the predominant type of nickel deposit in the Philippines. The type of weathering which dissolves silica and metallic elements from rock to produce limonitic and silicate nickel ores occur most frequently in tropical climates with high rainfall and with decomposing vegetation to provide organic acids and carbon dioxide in groundwater. Such deposits the ore in layers at varying depths below the surface. Nickel grade of lateritic ores usually ranges from 1-2%.

Extractive Metallurgy of Ferronickel

Nickel laterite ores have historically been treated almost exclusively by smelting processes and the industry is still predominantly pyrometallurgical. The rotary kiln – electric furnace smelting process is used almost universally for the production of ferronickel from oxide ores.

The development of nickel oxide ore smelting for ferronickel production has drawn heavily on iron and steel metallurgy. The separation of nickel from the refractory oxides is relatively simple because there are large differences in the free energies of formation of nickel oxide and the gangue components such as silica and magnesia. Adjustment of the reduction conditions permits the complete reduction of nickel oxide while limiting the degree of reduction of iron oxide, but a total separation of nickel from iron by selective reduction is not possible.

Nickel smelting is energy intensive since all of the free moisture and combined water have to be removed and all of the materials have to be first calcined and then melted to form the distinct slag and metal phases.

Conceptual/Analytical Framework

For the operations of a potential start-up nickel smelter to be in line with sustainable development, it must be efficient in energy usage. Energy costs from electricity, coal and bunker "C" oil should be closely monitored since they comprise about 50% of the total production costs of ferronickel.

In addition, particulate emissions which are the major negative externality in nickel smelting could be recycled by pelletizing to be utilized as a recycled raw material. Without pelletizing, the collected particulates would simply be accumulated to be landfilled to the solid waste dumping area. In other words, apart from preventing emissions, recycling these particulates reduces material intensity of consuming a non-renewable resource such as a nickel laterite mineral deposit.

Furthermore, it must strive for the minimization of environmental burdens. Land affected both by surface mining and disposal of solid waste product consisting of smelting furnace slag near the plant site should be restored to their original conditions. The other negative externalities should also be held to a minimum such as atmospheric acidification due to SO_2, global warming due to CO_2, human health hazards due to the possible presence of carcinogenic substances such as nickel inorganic and cobalt compounds.

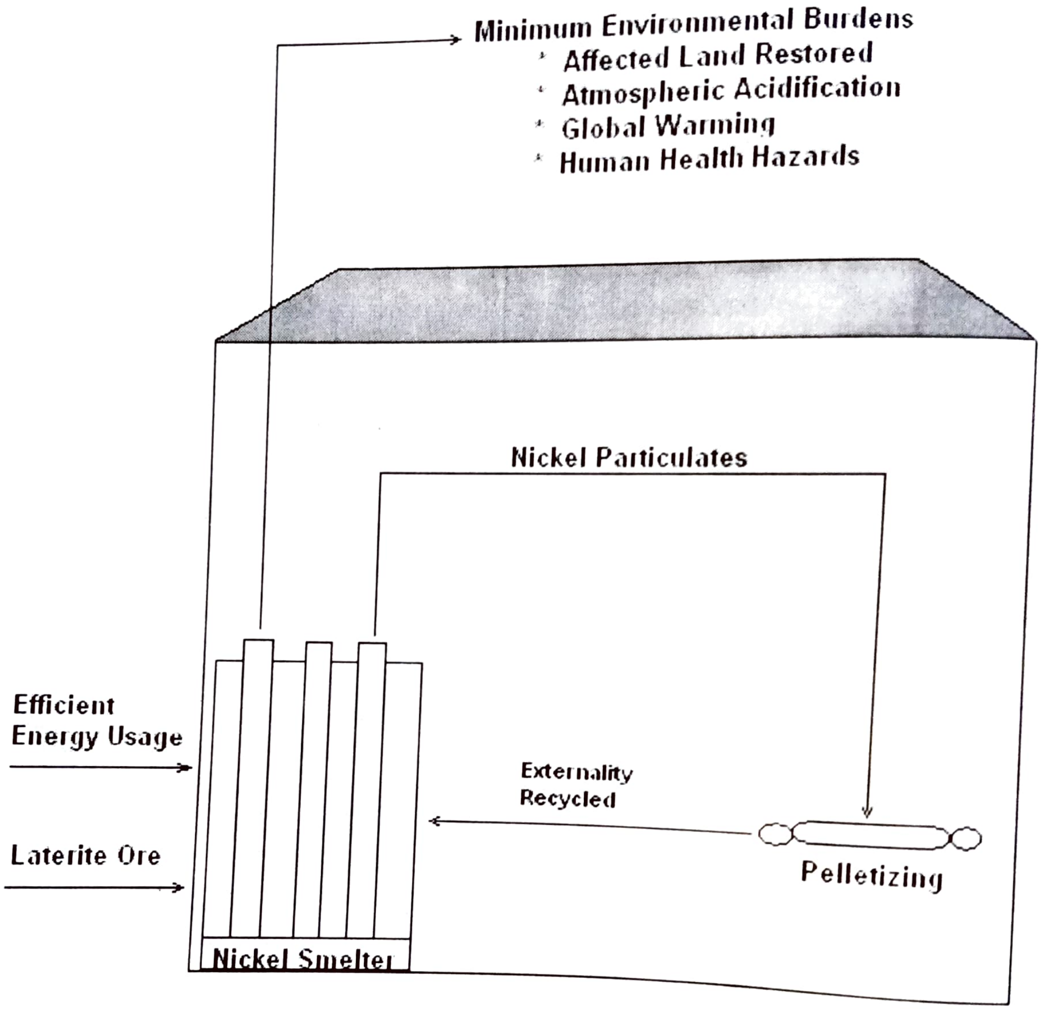

Figure 1. Enhanced Sustainability of a Start-Up Nickel Smelter

Methodology

1. Review of process flow and pertinent smelting reactions; The processes from the mine site up to the different stages in smelting is reviewed to highlight the sources of negative externalities, usage of resources and sources of environmental burdens.
2. Description of externalities and mitigating measures; The nature of negative externalities is described together with the proposed anti-pollution equipment.
3. Formulation of a set of sustainable metrics patterned after that of UK Institute of Chemical Engineers;
   3.1 Usage of Resources Metrics is developed for the following:
      a. Land use to reflect the fraction of land restored after having been affected by surface mining and dumping of solid waste product;
      b. Conversion ratio of laterite ore feed per ton of ferronickel product;
      c. Fraction of laterite ore feed in the form of dust recovered by pelletizing; and
      d. Breakdown of energy consumption in terms of electricity, coal, and Bunker "C" oil per ton of ferronickel product;

   3.2 Environmental Burdens Magnitude of environmental burdens such as atmospheric acidification due to SO_2 in Table 4, global warming due to CO_2 in Table 5 and human health hazards due to other substances in Table 6 can be assessed from the material balance based on the assay of laterite ore, coal and Bunker "C" oil in the feed mix.
4. Recommendation for Monitoring Frequency

Discussion and Recommendations

Flow Process

A generalized block flow diagram in the production of ferronickel from laterite ore which is to be surface-mined and then to be smelted is presented in Figure 2:

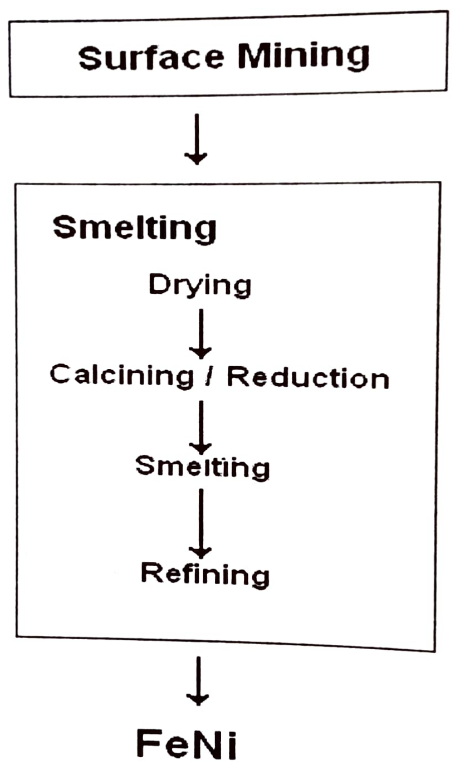

Figure 2. Block Flow Diagram of Ferronickel Production

Surface Mining

Laterite ore, being a mineral deposit that is close to the surface is extracted by surface mining. Heavy equipment, such as earthmovers, remove the overburden first, or, the soil and rock above the deposit. Next, huge machines, such as the dragline excavators, extract the mineral.

Smelting

After the required sizing/crushing and final blending with coal in the silos, the blended nickel ore is fed to the rotary kiln for pre-heating at 700 - 750°C and calcining at 1,000 – 1,200°C with an estimated residence time of 55 minutes. Apart from Bunker C which enters the kiln from the discharge end, coal is added as a reductant in the blended ore in order to attain the targetted temperature. This is to completely dehydrate the ore and to allow partial reduction of the metals to occur in the kiln. Such will reduce the energy consumption in the subsequent smelting operation. Under optimum conditions, up to 40% of the nickel is reduced to metal while the iron oxide is reduced to iron (II) oxide (FeO) according to the following reactions:

$$NiO + C \longrightarrow Ni + CO \qquad [1]$$

$$Fe_2O_3 + C \longrightarrow 2FeO + CO \qquad [2]$$

The calcined ore is then fed to the electric arc furnace for smelting maintained at a temperature of 1,600°C to permit the distinct separation of the slag and metal phases. Virtually all of the nickel is reduced to metal to yield a ferronickel grading of about 20% Ni while the slag contains only 0.1% Ni. Also, FeO is reduced according to the following reaction below:

$$FeO + C \longrightarrow Fe + CO \qquad [3]$$

In alloy refining, sulfur is removed by the addition of calcium carbide to the molten ferronickel according to the reaction below:

$$CaC_2 + S \longrightarrow CaS + 2C \qquad [4]$$

Externalities and Mitigating Measures

Since nickel has a relatively high melting temperature (1455°C), it is very unlikely to occur in gaseous (vapor) form at normal atmospheric temperatures. The major externality, then, in nickel smelting is particulate emissions specifically in the form of dust. Dust are small solid particles created by the breakup of larger masses through processes such as crushing, grinding, etc. Dust are capable of temporary suspension in air. Hence, they do not diffuse but settle under the influence of gravity according to Peavy. [7]

As compared to particles larger than 50 μm which can be seen with the unaided eye, nickel particulate emissions are mostly of about 30 microns in diameter with small fractions in the 10 and 20 micron diameter size ranges in an exposure assessment of airborne nickel at Paducah, Kentucky, USA. [8]

The discharge of particulates can be controlled by anti-pollution devices such as gravitational settling chambers, centrifugal collectors such as cyclones, bag filters, and electrostatic precipitators.

Particulates emanating from the blended nickel ore during feeding to the rotary kiln could be trapped in a gravitational settling chamber. After settling to its bottom, the particulates are collected and conveyed back to the rotary kiln.

The particulates coming from the discharge end of the rotary kiln could initially pass through a cyclone. While cyclones are usually simple to operate and have minimum maintenance costs, high dust collection efficiencies can only be achieved if the dust particles are above 10 microns in size. The cyclone functions as a pre-collector to reduce the dust burden of the final-stage dust collector which is the electrostatic precipitator in order to increase the over-all collection efficiency. These same devices in operation on similar industrial sources have demonstrated efficiencies ranging from 95% to 99% as gathered by an US EPA Report. [4]

Flue gases from the furnace could be encapsulated by bag filters. Modern fiber technology has produced fabric-type filter suitable for high temperature applications as cited by Encarta. [9]

To insure complete containment of the particulates, however, it is recommended that areas where fugitive emissions are likely to occur should also be encapsulated by bag filters.

Lastly, the proposed mix of anti-pollution devices should be able to handle SO_2 emissions (i.e., through the use of scrubbers or a flue gas desulphurization system).

Environmental Sustainability Metrics

The following environmental sustainability metrics is patterned after that of the Sustainable Development Progress Metrics developed by UK Institution of Chemical Engineers which is recommended for use in the process industries. [2] Land occupied by the plant site is the area where the plant facilities are located.

Table 1
Land Use

Land occupied by plant site	______ha
Land affected by dumping solid waste product near plant site	______m^2/year
% affected land restored to original condition	______%
Land affected by surface mining	______ha/year
% affected land restored to original condition	______%

Another portion of land near the plant site shall be affected since it shall be utilized as dumping area for a significant volume of solid waste product consisting of smelting furnace slag. The % affected land restored to its original condition is the fraction rehabilitated during a given reporting period.

At the mine site, large areas of land shall be affected by surface mining where devastated areas, called spoil banks are left behind.

Rehabilitation would consist of ground and slope stabilization, re-vegetation and reforestation.

Again, the percentage affected land restored to its original condition is the fraction rehabilitated during a given reporting period.

This assumes that land affected for both disposal of solid waste product and surface mining for a given reporting period should be scheduled for rehabilitation within the same reporting period.

Table 2

Quantity of Laterite Ore Used/Recovered as Pelletized Particulates

Total laterite ore feed	_____tons/month
Laterite ore feed/ton of ferronickel product	_____tons/ton
Total recovered pelletized particulates	_____tons/month
Fraction of laterite ore feed recovered by pelletizing	_____ %

Total laterite ore feed is the weight of the ore fed to the nickel smelter. In a given reporting period, the ratio of this figure to the ferronickel production gives the laterite ore feed per ton of ferronickel product.

Since the nickel content of particulates trapped and collected by anti-pollution devices in smelting would probably average that of the ore, could be as high as 2.4% nickel, it would be economically justifiable to recover them as a recycled feed. They are pelletized into larger, more suitable lumps of appropriate size and strength since the particulates are too small to be utilized as rotary kiln feed. In pelletizing, a suitable binder and water are added to the particulates or ore fines which are fed into an inclined rotating drum or disk. These green pellets may subsequently be fired in a furnace to increase their strength.

Total recovered pelletized particulates is the weight of particulates which has been collected and pelletized. The ratio of this figure to the total laterite ore feed for a given reporting period gives the fraction of laterite ore recovered by pelletizing.

Table 3
Energy Consumption

Source	Energy Value	Quantity Used/Month	Energy Usage Rate / Month
Electricity	______GJ/kWh	______kWh	______GJ
Coal	______GJ/ton	______tons	______GJ
Bunker "C" Oil	______GJ/m^3	______m^3	______GJ
Total			______GJ
Energy usage per ton of ferronickel product			______GJ/ton

The smelting process requires energy for size reduction, heating, chemical reactions, mixing and phase separation. The required energy may be in the form of chemical energy, heat from the combustion of fuels, and electrical energy, For example, in rotary kiln operations, heating is done principally by the combustion of a hydrocarbon, the intermediate reduction is brought about by the partial burning of added coal.

In smelting, the energy input to the charge is provided by radiation from the electric arcs around the tips of the electrodes and by the heat generated in the slag by resistance heating due to the flow of current through the slag layer between the electrodes. Since the electrical resistivity of the metal layer is much lower than that of the slag, very little heat is generated in the metal layer, which must therefore receive heat by conduction and convection transfer from the overlying slag layer as gathered from Unpublished Materials in the Extractive Metallurgy of Nickel. [5]

From literature and empirical data, energy values are obtained for each source of energy listed in the Table 3. Next, the quantity used per reporting periods are monitored by electric meter reading for electricity and appropriate inventory measures for coal and bunker "C" oil. For each source of energy, the energy value is then multiplied by the quantity used to come up with the usage rate per reporting period. These are then summed up to get the total usage rate for all the energy sources per reporting period. Finally, the ratio of total usage of energy to the ferronickel production per reporting period is computed.

The pyrometallurgical production of ferronickel is extremely energy intensive and energy costs can account for 50% of the production cost of ferronickel. Energy is consumed in drying the moist ore, in calcining the dried ore to remove the chemically bound water, in heating the charge to melting temperature, and in smelting. The distribution of energy consumption in a typical ferronickel smelter is indicated in the following typical data: [5]

	GJ/ton ore
Drying	1.3-2.0
Preheating and prereduction	3.3-4.2
Electric smelting	1.4-2.2
Other electrical energy	0.22-0.29
Total	6.22-8.69

Electrical energy for the electric furnace actually accounts for only 25-30% of the total energy consumption in a smelter, while the rotary kiln operation consumes about 50% of the total energy required.

Table 4
Atmospheric Acidification Burden

SO_2 atmospheric acidification burden(AAB)	________tons/month
SO_2 AAB/ton of ferronickel product	________tons/ton

The atmospheric acidification burden (AAB) caused by the emission of sulfur dioxide (SO_2) is its total emission for a given reporting period. The ratio of this figure to the ferronickel production gives the SO_2 atmospheric acidification burden (AAB) per ton of ferronickel product for that particular reporting period.

Fuel combustion in the burning of coal and Bunker "C" oil during calcining/reduction at the rotary kiln will generate SO_2.

Sulfur dioxide (SO_2) is a colorless, nonflammable, and nonexplosive gas with a suffocating odor. The simplified mechanism for the formation of SO_2 according to Kiely is [10]

$$S + O_2 \longleftrightarrow SO_2 \qquad [5]$$

Reacting with other components in the atmosphere, SO_2 can produce sulfur trioxide (SO_3) and droplets of sulfuric acid (H_2SO_4), in the presence of sufficient water, according to the following reactions

$$2SO_2 + O_2 \longleftrightarrow 2SO_3 \qquad [6]$$

$$SO_3 + H_2O \longrightarrow H_2SO_4 \qquad [7]$$

Thus, H_2SO_4 is the compound most commonly found in the atmosphere, rather than SO_3.

Table 5
Global Warming Burden

CO_2 global warming burden (GWB)	_______tons/month
CO_2 GWB/ton of ferronickel product	_______tons/ton

The global warming burden (GWB) caused by the emission of carbon dioxide (CO_2) also during calcining/reduction is its total emission for a given reporting period. The ratio of this figure to the ferronickel production gives the CO_2 global warming burden (GWB) per ton of ferronickel product for that particular reporting period.

CO_2 is one of the major greenhouse gases. It is generated from the combustion of carbon fuels according to the following reactions by Kiely [10]

$$2C + O2 \longrightarrow 2CO \quad [8]$$

$$2CO + O_2 \longrightarrow 2CO_2 \quad [9]$$

The first reaction is about 10 times faster than the second. Thus, CO is an intermediary product but may show up as an end product is insufficient O_2 is available for the second reaction.

Table 6
Human Health Burden

Benzene Equivalent Human Health Burden (HHB)			______tons/month
Benzene Equivalent HHB/ton of ferronickel product			______tons/ton
Substances	Potency Factor PF	Weight(tons/month)	HHB/month
Nickel & Inorganic Compounds	160	________tons	______tons
Cobalt & Compounds	160	________tons	______tons
Total			________tons

The human health burden or carcinogenic effects caused by substances that may be emitted during nickel smelting is expressed in terms of benzene equivalent. Other substances have assigned potency factors relative to benzene as derived from the Occupational Exposure Limits set by the UK Health and Safety Executive. [2]

For each substance present, its potency factor is multiplied with actual tons emitted to come up with the benzene equivalent HBB per reporting period. These are then summed up for all the substances present.

Finally, the ratio of the total benzene equivalent HBB to the ferronickel product for a given reporting period is obtained.

Table 7
Recommended Frequency of Monitoring

Environmental Sustainability Indicators	Frequency
Land Use	Every Year
Quantity of Laterite Ore Used/Recovered as Pelletized Particulates	Every Month
Energy Consumption	Every Month
Atmospheric Acidification Burden	Every Month
Global Warming Burden	Every Month
Human Health Burden	Every Month

Of the environmental indicators, only the land use is deemed practical to be monitored every year. The integrated rehabilitation of devastated areas is considered a long term activity with its benefits realized over the long term.

The operational indicators comprising the quantity of laterite ore used/recovered as pelletized particulates and energy consumption should be monitored every month in order to provide immediate management feedback for operational efficiency in terms of material usage and energy consumption.

Lastly, the environmental indicators that comprise the atmospheric acidification burden, global warming burden, and human health burden should also be monitored every month so that mitigating measures could immediately be implemented should problems arise.

Conclusion

Potential nickel smelters soon to be established in the Philippines is a welcome development. However, their operations must be in line with the new global ethic of sustainable development. Towards this end, the application of environmental metric indicators would be of great value to help achieve a more sustainable operation in terms of efficient usage of resources and to minimize the burden on the environment.

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