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A PROPOSED FRAMEWORK OF ECO-EFFICIENCY FOR THE NONFERROUS METAL MINING SECTOR

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ABSTRACT

The most effective method of promoting sustainable development in business is through the adoption of eco-efficiency. This management strategy, of which the principles are broad in scope, categorizes activities that protect the environment and, at the same time, reduce corporate costs. In the case of the nonferrous metal mining sector, which has traditionally been regarded as being a "dirty" industry, the integration of eco-efficiency into business practices would help lead to a reduction in environmentally damaging activities in the areas of material inputs, energy use, waste consumption, and resource use. This article discusses the importance of eco-efficiency as a tool for environmental management in the nonferrous metal mining industry. It summarizes the evolution and principles of eco-efficiency, identifies important environment problems related to this particular sector of mining, and develops a sample eco-efficiency framework as a means to prevent and reduce the impacts of these problems.

INTRODUCTION

In business, the debate regarding what might be a broadly accepted way of promoting, measuring, and monitoring sustainable development has deep roots. The traditional ideas and methods that have fueled sustainability in industry have failed to produce significant improvements in environmental quality. In this article, it is argued that the most effective means of initiating a mass flow of sustainability in business is to adopt a vision of eco-efficiency. This management strategy involves the continuous search and adoption of corporate strategies that are environmentally sound and are more cost-effective for firms.

The movement toward sustainability must begin in the primary sector. Nonferrous metal mining is a staple component of global industrial primary production and all of its industries generate a common set of environmental impacts. Within the industry, a greater emphasis must be put on controlling environmental problems like materials pollution, fossil fuel use, and toxic contamination, which could help direct the mining industry toward sustainability. This article demonstrates the usefulness of eco-efficiency as a (sustainable development) management tool in the nonferrous metal mining industry. It details the evolution of eco-efficiency in business, summarizes key environmental issues in the sector, and presents a sample framework of eco-efficiency for nonferrous metal mining firms.

BACKGROUND

Nonferrous Metals and Their Industrial Uses

A nonferrous metal is any metal that does not contain iron. The division between "ferrous" and "nonferrous" arises from the fact that of the dozens of metallic elements used industrially, iron (ferrous) accounts for more than 90 percent of total production [1]. The nonferrous group contains a diverse collection of metals that vary between two extremes based upon their abundance and ease of extraction, exemplified on the one hand by gold and platinum, which are scarce but easily reduced into metallic state, and on the other by aluminum and magnesium, which are abundant but difficult to reduce.

Nonferrous cadmium, nickel, copper, zinc, tin, and lead have been in use for at least 5000 years, particularly to make alloys: homogenous compounds, mixtures, or solutions that comprise two or more metals and do not separate under natural conditions [2]. The melting point of an alloy is usually lower than those of its base metals but is typically harder and stronger. The most common nonferrous alloys are those of copper, in particular brass and bronze. Brass is a mixture of copper and zinc and, because of its resistance to corrosion, is used for plumbing, hardware, brazing, and as a wearing surface. Bronze is an alloy of copper and tin and is much harder than brass. It is used for special purposes such as gears, bearings, and bushings, where toughness and antifrictional properties are desired [3].

With the exception of nickel, which was first identified as a specific element in 1790, the mining of nonferrous base metals—copper, nickel, lead, and zinc—has occurred for centuries. Base metal ores categorize the most common nonferrous minerals, and vestiges of their metallurgy date back to approximately 6300 BC [4]. The advent of industrialization, however, made the production of these and additional nonferrous metals (gold, silver, tin) quantitatively significant, when they were first extracted in purer forms. They have since been used as component parts for a wide range of different products, from electric cables, jewelry, tin cans, and batteries to catalysts in the chemical industry (Table 1).

Table 1. Some Industrial Uses of Selective Nonferrous Metals

Nonferrous Mineral	Principal Manufacturing Use of Metal
Aluminum (Al)	Grinding wheels, utensils, paint additive
Copper (Cu)	Plumbing, roofing, electrical wire
Nickel (Ni)	Plating agent, coins, steel alloys in machinery
Lead (Pb)	Batteries, gasoline additive, vat liners
Zinc (Zi)	Galvanizing agent, roofing, drain pipes
Gold (Au)	Jewelry, metal plating
Silver (Ag)	Silverware, photographic materials
Magnesium (Mg)	Flares, fireworks, lightweight castings
Tin (Sn)	Tin plating, solder, alloying agent
Tungsten (W)	Alloying agent, acid-resistant special steel

Mining Nonferrous Metals

Four main stages comprise the production process of nonferrous metals: exploration, extraction, smelting, and refining. Searching for the mineral deposit is the beginning stage in any nonferrous metal extraction process. Potential sites are drilled and excavated to determine ore quality and the extent of deposits. If prospective tonnage of the reserve is sufficient to justify investments in mine development, plant construction, and equipment investment, operations commence [5].

The extraction process follows exploration. Techniques are determined based upon the nature of the environment and the characteristics of the mineral reserve. When deposits are located near the surface, a firm employs surface mining methods that require excavation of huge plots of land and generate large volumes of waste rock [6]. When ore bodies are buried deeper in the earth, underground mining techniques are used. These include the sinking of mine shafts to deposit depths, the preparation of slopes for drilling, and the construction of facilities for mineral removal.

Following extraction, nonferrous metals require further treatment to reach their purest states. Ores are grinded, crushed, and separated to produce a powder of higher metal content, which is then smelted and refined to produce the final metal product [7]. Smelting processes separate crushed ore into a composite metal product often containing traces of other minerals. Refining, which involves an electrolytic process, produces the "pure" metal product: the raw input for manufacturing.

All nonferrous mining operations can cause considerable damage to the environment. The stricter environmental legislation of recent years has led to minor improvement in environmental "behavior" within the industry but many activities are still causing considerable impact to the environment. It is suggested in this article that the "best" way to surpass the environmental compliance stage in the nonferrous mining industry is to demonstrate that adopting environmentally sound practices saves company money.

ECO-EFFICIENCY

Sustainable Development in Business

In 1987, the Brundtland Commission, in its landmark report *Our Common Future,* introduced the idea of sustainable development—"meeting the needs of the present without jeopardizing the needs of future generations"—as means for resolving interrelated environmental and socioeconomic problems [8]. The United Nations responded to the Brundtland Report by convening the Earth Summit in Rio de Janeiro, 1992, a momentous gathering that coordinated the efforts of scientists and social service organizations and which established the blueprints for a new series of laws that many international governments felt would move the world toward sustainable development. Since Rio, there has been a significant change in corporate attitude toward the environment. Many companies have not only restructured operations to comply with new environmental legislation but have performed several voluntary measures in an attempt to further reduce pressures from governments and stakeholders [9]. In the process, these firms have dramatically improved their environmental images and performances.

Initially, the business community was cautious about how to react to the idea of sustainable development. Firmly wedded to their operations that had caused the environmental crisis in the first place, corporations had problems conceptualizing sustainable development and failed to see its applicability in industry. However, in recent years, many companies around the world have begun recognizing the usefulness of integrating sustainable development into business practice after realizing that the adoption of "green" practices positively affects the bottom line. In their development of sustainable strategies, the managers, employees, and executives of these firms are attempting to answer the following questions:

- What are the most pressing environmental issues facing the company?
- From an environmental perspective, in what areas is the company being most pressured to improve its performance?
- Overall, how can sustainable development practices benefit the company?
- What sustainable development strategies are most effective (economically) for the company?
- How should the company go about implementing sustainable development?

Eco-efficiency is the primary way in which business can contribute to the concept of sustainable development. The pursuit of this management philosophy not only helps protect the environment but also creates a wealth of benefits for any firm throughout the industrial supply chain (Table 2). Eco-efficiency does not require companies to abandon their current practices and systems but calls for them to restructure them in order to achieve higher levels of economic and environmental performance through continuous improvement [10].

The World Business Council for Sustainable Development (WBCSD) and Eco-Efficiency

"Eco-efficiency" was first used by the Business Council for Sustainable Development (BCSD) in its report *Changing Course,* 1991, which the U.N. requested as a business input to the Rio process. The BCSD was the brainchild of a wealthy Swiss businessman, Stephan Schmidheiny, who was appointed by Maurice Strong, the Secretary General of the Earth Summit in Rio, as his principal advisor on business and industry [11]. In 1995, the BCSD merged with the World Industry Council for the Environment (WICE)—which was established at the beginning of 1993 to follow up the policy implications of the Earth Summit—into the World Business Council for Sustainable Development (WBCSD),

Table 2. Examples of How Eco-Efficiency Can Benefit a Firm

	Economic Benefit
1.	Creates a better relationship with banks, which are more willing to lend to "cleaner" companies.
2.	Creates a better relationship with insurers, which are more willing to insure "cleaner" companies.
3.	Motivates a company and its employees to become more innovative on many fronts.
4.	Results in a reduction in government pressures.
5.	Leads to a reduction in energy costs, materials costs, and resource costs.
6.	Leads to improved efficiency of operations at all levels of business.
7.	Creates shareholder value.
8.	Leads to increased recyclability and recovery, which, in turn, reduces waste disposal costs.
9.	Contributors to "green consumerism" demands.

an organization that aims to "provide business leadership as a catalyst for change" in the achievement of sustainable development and to "promote the attainment of eco-efficiency through high standards of environmental and resource management in business" [12]. Today, the WBCSD is a coalition of 125 leading international companies united by a shared commitment to the environment and to the principles of economic growth and sustainable development [13]. Its members are drawn from over thirty-three countries representing more than twenty major industrial sectors, and are at the forefront of business response to the challenges arising from Rio. They play an important role in developing closer cooperation between business and governments, and in encouraging high standards of environmental management in business itself [12].

During the course of a series of multistakeholder workshops held by the WBCSD between 1993 and 1996, the following definition of eco-efficiency emerged:

> The delivery of competitively priced goods that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the lifecycle, to a level at least in line with Earth's carrying capacity [14].

Eco-efficiency is a task for each entity within society [15]. At the corporate level, it embraces strategies in the areas of "pollution prevention," "waste reduction," "source reduction," and "cleaner production," all of which capture the idea of *pollution reduction through process change,* as opposed to traditional reactionary "end-of-pipe" approaches to tackling environmental problems [16]. In summary, eco-efficiency is simply producing more from less, and characterizes those activities that create economic value while continuously reducing ecological impacts and the use of resources.

Analysis of Eco-Efficiency and Its Principles

The WBCSD has identified seven components of eco-efficiency that sustainable businesses should be taking into account when developing products, introducing process changes, or taking other actions with environmental implications. Each principle is wide-ranging in scope and can be applied to almost any sector of industry.

1) Reduce Overall Material Intensity

Since mass inputs of materials occur at every stage of a product's lifecycle, a large quantity of waste is produced. The resulting costs of pollution control are passed down the industrial chain and are eventually absorbed by the consumer. Thus, using raw materials more efficiently and sustainably benefits the environment and reduces expenses for all parties [17].

2) Reduce Overall Energy Intensity

Like material inputs, energy inputs are required at every stage of the life cycle. Power production generates air pollution—notably sulphur dioxide, nitrous oxides, and suspended particulates—and solid wastes [18]. The energy intensity of a product refers to the amount of energy that is needed for assembly from raw materials plus the energy used for consumption and disposal.

3) Reduce the Dispersion of Toxic Materials

Industrial processes use harmful toxics that can either quickly break down in the biosphere or remain unchanged and persistently bioaccumulate in the environment [19]. In addition, poisonous chemical agents are used in many industrial processes. Minimizing the use and production of toxic agents is an important part of environmental protection in any industry.

4) Increase Recyclability

This includes anything from industrial wastes, through materials, to decommissioned products. Reusing materials reduces both the consumption of resources and energy and the environmental impacts caused by waste disposal [20]. The basic method for materials reduction is the "4R strategy" (repair, re-use, remanufacturing, and recycling), which, if pursued in a fashion that requires less energy and generates less pollution, contributes to eco-efficiency [21].

5) Maximize Sustainable Use of Renewables

Fossil fuels—coal, oil, and natural gas—are the most common energies used in industrial society [22]. These resources are finite in availability and are continuously being stressed. Using renewable or replenishable resources in place of exhaustible resources reduces environmental impacts throughout the product lifecycle [23]. Maximizing sustainable use of resources is an important component of sustainable development (hence, eco-efficiency) and includes substituting renewable energies for conventional sources, redesigning products to use more abundant input materials, and maximizing usage of passive heat.

6) Extending the Durability of Products

Product durability is the ability of a product, its parts, components, and materials to resist the action of degrading agents over a period of time [24]. Thus, redesigning a product into a more durable state creates a more efficient good, and results in using less material and energy inputs throughout its lifecycle. The process of engineering longer-lasting, less energy-intensive products is often referred to as "ecodesign," and accounts for both the inputs to goods and the efficiencies of the equipment producing them [25]. Some of the methods used to extend product durability include: reprocessing materials, improving product maintenance, and educating customers.

7) Increasing Service Intensity of Goods and Services

Increased service intensity requires creating value while reducing environmental impact. Efforts can be made in any business area—from design to transportation—that can contribute to increased value for customers [26]. Increasing the service intensity of goods and services can be achieved in a variety of ways, including redesigning products to meet additional future needs of customers, providing a "take-back" service to help deal with customer disposal problems, and devising more efficient transportation schemes to market.

In this study, the WBCSD's seven principles of eco-efficiency were used as the basis for developing a sample framework of eco-efficiency for the nonferrous mining sector. Key environmental issues were first identified and summarized to indicate what challenges the industry is facing. Once problems were recognized, the relevance of each principle to nonferrous metal mining was discussed and strategies were devised.

THIS STUDY

Major Environmental Issues: Nonferrous Mining

The first step in developing any framework of eco-efficiency for any industry is identifying major environmental issues. Since nonferrous metals are rarely found in homogenous deposits, particular extraction, excavation, and production processes are required, which have the potential to cause many environmental problems. Among the most significant are:

1. Toxicity of metals. Nonferrous mining operations threaten natural waters, soils, plant life, and the health of animals and humans [27]. When mixed with water, nonferrous minerals can be highly toxic. Trace elements—notably lead, cadmium, arsenic, and mercury—occur in both ground and surface waters due to natural processes [28]. However, nonferrous mineral deposits and associated smelting and metal processing activities have increased "loadings" of these trace elements in the biosphere. For example, in many mining areas increased concentrations of cadmium and lead have accumulated in surface soils, private drinking wells, and creeks and rivers. Both elements are found naturally in soils but, in high doses, can poison mammals directly and stimulate leaf chlorosis in plants. Untreated mine waters resulting from nonferrous production causes additional damage to surface waters, including poisoning and depleting populations of benthic organisms, dissipating spawning gravel for fish, and restricting the use of water for irrigation, livestock watering, or industrial supply [29].

2. Chemicals used in refining. Potentially toxic chemicals are often used in the processing of ores. In gold processing, for example, cyanide has been the leach reagent of choice for over 100 years [30]. Resulting effluents, however, contain waste cyanide and thiocyanate ions, which are noxious to the

environment and require removal or neutralization before effluent discharge. Ultraviolet light decomposes thiocyanate into cyanide, which, in high concentrations, is toxic to aquatic life [31]. The use of mercury in gold and silver separation processes is well documented as well. Mercury "wets" and adheres to metallic gold and silver, forming pasty amalgams, which is then roasted, generally in open air, emitting mercury vapor into the atmosphere [32]. During the amalgamation process, metallic mercury is lost to rivers and soils, where it is then transformed by microorganisms into stable and highly toxic methylmercury (Me-Hg). This species of mercury accumulates strongly in aquatic biota, resulting in contamination of fish, bird, and, eventually, human tissue [33].

3. Toxic Air Emissions. The control of air pollutants from metallurgical processing has long been a troublesome problem. Most nonferrous metals occur as sulphides, which are usually accompanied by iron sulphides. Thus, when nonferrous ores are smelted, enormous quantities of sulphur dioxide is emitted into the atmosphere [34]. The major problem associated with mass outputs of sulphur dioxide is that it is the principal component of acidic deposition. Once fallen, acidic deposition lowers pH levels in soils and surface waters, making habitats toxic for plants and benthic organisms. In the past, the solution was to construct larger smokestacks but this only resulted in dispersing pollutants over further distances [35].

4. Acid Mine Drainage (AMD). The process of separating valuable ore from uneconomic gangue generates enormous amounts of waste rock (tailings) containing iron sulphides. These easily oxidize into sulphuric acid, which can solubilize residual metal when flushed with snowmelt or rain, creating Acid Mine Drainage (AMD) [36]. The discharge of AMD introduces large quantities of metals to streams and aquifers that become associated with sediments and soil particles [37]. Ensuing acidity, metal toxicity, and sedimentation processes cause numerous chemical, physical, biological, and ecological impacts to the environment (Table 3). Poorly buffered waterbodies, which possess low concentrations of the neutralizing agent bicarbonate, are ill equipped for AMD and, when bombarded, pH lowers, all aquatic life disappears, and riverbeds become coated with rust-like particles [38].

Table 3. Examples of Major Impacts of Acid Mine Drainage (AMD)

Chemical	Physical	Biological	Ecological
Increased acidity	Turbidity	Reproduction	Habitat modification
Increased metal solubility	Decreased light penetration	Respiration	Loss of prey
Destruction of bicarbonate systems	Sedimentation	Migration	Elimination of sensitive species

5. Mine reclamation. Mining activities require excavation of large tracts of land and removal of large quantities of vegetation, and in the process, initiate a chain of soil, water, and wind erosion. Therefore, after a mine site is closed down, measures should be taken to reclaim the site and restore what was eliminated as a result of industrial activities [39]. Reclamation involves buffering polluted waters, revegetating lands, stabilizing hillslopes, and tailings treatment.

An Eco-Efficient Framework for Nonferrous Metal Mining Industries

Having identified the key environmental issues of nonferrous metal mining, a sample framework of eco-efficiency is now proposed. Sample strategies are provided under each principle and appropriate examples are given.

1. Reduce Material Intensity:

- Decrease water consumption

  Nonferrous metal mining companies can reduce water consumption, the resource that is used the most in operations. It is used 1) in crushing, grinding, and milling processes as a coolant; 2) as a concentrate for mineral and chemical mixtures; and 3) as a transport medium for tailings slurries [40-42]. Continuous tapping of "virgin" water sources can damage ecosystems and create large water treatment and remediation costs. Wastewater can be recycled by utilizing tailings ponds, which effectively "separate" mining slurry into sediments; sediments sink to the bottom and surface water can be "skimmed" and reused [43]. Alternatively, water can be recovered by feeding slurry into a tank and separating water from sediment using a two-stage operation. First, thickening occurs where particles gravitate slowly downward and settle out of the liquid in a large tank. Second, vacuum filtering occurs, where a porous sheet is mounted to the "mud" and squeezed to release remaining water [44].
- Reuse mining wastes

  Waste mining tailings can be recycled and reused in a variety of ways. For example, in gold mining waste pyrite tailings are used as energy-feed for autoclaves. These tailings often contain unrecovered gold and their use would allow a company to recover the unused resource and allow it to avoid the costs of steam generation for the autoclave [45]. In the case of nickel refining wastes are often loaded with nickel sediments. Reclaiming nickel from waste reduces the flue dust and other waste streams [46].
- Install an environmental management system (EMS)

  Efficiency of production increases with the integration of an EMS into business operations. An EMS involves the auditing of operations and helps an organization better manage its liabilities, continually improve its environmental performance, and potentially contributes to profitability [47]. Auditing results in more effective monitoring of industrial operations, which in turn improves management and regulation of material inputs at all levels of operations.

2. Reduce Energy Intensity

- Reuse waste heat

  Waste heat energy can be recovered for reuse in a number of processes. Heat is used principally for smelting ore to remove desirable metals. The waste heat from exhaust gases can be recovered to preheat combustion air [48]. Alternatively, it can be used directly to preheat ore or ore concentrates fed to smelting processes. Ancillary uses of waste heat include: heat for building, plant facilities, processed water, and "mining" towns.
- Use more energy-efficient technologies in industrial processes

  Industrial processes are energy-intensive and require mass quantities of fossil fuels. However, many energy-efficient strategies have been developed that can help reduce corporate costs and environmental impacts [49]. In the nonferrous metals industry, many energy-efficient technologies are available that use less power. For example, the use of electrotechnologies in place of fossil fuel-based smelting processes uses 50 to 90 percent less energy and provides a higher heating rate. Another example of a more energy-efficient technology is air dampers, which can be used in holding furnaces (which "hold" the metal until it is cast). When these furnaces are on low fire, recoverable heat is lost. Installing an air damper, which creates backpressure along furnace openings, prevents heat from escaping [50].
- Maximize the use of "waste" energies

  Energy can be derived from perceived industrial "wastes." For example, waste sulphur, which occurs in gaseous form as sulphur dioxide, can be collected and burned as a power source for furnaces and pumps [51]. Furthermore, biomass (trees and vegetation) sources removed during exploration phases can be dried and then used for heating, furnace blasting, and as an electricity source.

3. Reduce the Dispersion of Toxic Materials.

- Improve treatment of AMD

  AMD is inevitable with any nonferrous mining operation. However, through improved monitoring practices and use of biological environmental indicators, acid mine water can be detected and remediated at a faster rate. Lime and limestone should be placed in receiving streams to buffer incoming AMD. The calcium carbonate of lime neutralizes ferric acid and dissolved sulphur dioxide [52]. In addition, passive treatment schemes—naturally occurring geochemical and biological processes—should be used to improve the quality of recipient waters. Bacteria, algae, and plant residues can help maintain pH levels and reduce dependence upon chemical agents [53]. Reacting quickly to AMD before it spreads further into the aquatic ecosystem is less costly for a firm.

- Investment in "scrubbers" for removal of acid gas

  Polluting industries are assigned quotas for various toxic air emissions and sulphur dioxide is one of the pollutants that is monitored by local environmental groups and government ministries. The installation of scrubbers in smelting smokestacks helps reduce the quantities of gaseous sulphur dioxide emitted into the atmosphere. These machines absorb emissions released from smokestacks and first separate gaseous solutions and solid particles. The scrubber then uses a filtration mechanism to the gas and neutralizes it with lime hydrate. The "clean" gas is then released into the air. Highly advanced scrubbers can reduce airborne sulphur dioxide by 90 percent, and, in turn reduce scrutiny from government and lobbying groups [54].

- Improve management and treatment of toxic agents

  Chemical agents like mercury and cyanide must not be mismanaged. Chemical disasters in the past have contaminated considerable tracts of ecosystems and have cost companies millions of dollars in cleanup. Avoiding these disasters can be best accomplished by eliminating toxic agents at point sources or neutralizing them before environmental discharge. Many cost- effective methods exist to treat toxics. For example, Figueroa had identified a variety of methods by which cyanide can be treated biologically [55].

4. Enhancing the Recyclability of Materials

- Chemical recycling

  The opportunities for chemical recycling in nonferrous metal production range from the chemicals used for refining to the "waste" toxics generated after smelting processes. In the case of mercury, which is used for amalgamating gold ores, biochemical reduction methods can be used to recover waste mercury from streams. Bacteria reduce the mercury salts from waterbodies into a mercury metal solution. Metallic mercury is then recovered directly using gravity separation techniques [56]. During the concentrating processes of nonferrous metals like copper, chromium, and zinc, organic surfactants are used in the treatment of wastewater [57]. Surfactants are used to separate the water from toxic heavy metal ions before water is discharged. The organic surfactants, which are toxic in the natural environment, can be removed from wastewater using heat, and then reused.

- Recover and reprocess waste metal from streams

  Many nonferrous metal particles exist in crushed gangue rock. After refining, it is mixed with water and discharged into streams. These trace metals, which are toxic to aquatic invertebrates in high concentrations, can be removed using a variety of methods. Similar magnetization processes to those used in scrap metal yards can be used to remove fine nonferrous particles from lakes, ponds, and rivers [58]. Chemical processes can also be used. Chemical precipitation techniques, along with standard hydrometallurgical and pyrometallurgical processes, can remove metal ions from aqueous solutions by transforming them into solid insoluble compounds, which can then be easily collected using physical processes [4].

5. Maximize the Sustainable Use of Renewables

- Exploit "passive" energies in industrial processes
  Renewable energies can be harnessed for use in the nonferrous metal mining industry. For example, given the quantity of energy required for water heating in refining processes, the use of a passive solar heating system could reduce use of fossil fuels and improve water heating efficiency [59]. Solar panels can also be used for lighting, electricity, and for machine power.
- Substitute renewable sources for coal
  The primary energy source used in mining operations is coal. Coal contains enormous quantities of sulphur and when burned produces sulphur dioxide [60]. By substituting biomass resources for coal in furnaces, less gaseous sulphur is produced which would benefit both a company economically and the environment aesthetically. Since many mining operations are located near river bodies, turbines could help deliver "renewable" power and help replace traditional polluting fossil fuels.
- Use low sulphur coals
  Utilizing coal for energy purposes is inevitable in all mining operations. However, in order to minimize sulphur emissions to the atmosphere, low sulphur coals should be used. Anthracite coals contain the highest sulphur contents but are preferred because it possesses the highest carbon content [61]. However, these coals can be easily replaced with subbituminous coals, which have the lowest sulphur content. Although subbituminous coals have the lowest heat values, these, along with supplementary renewable energies, could generate the equivalent heat produced by anthracite coals.

6. Extending the Durability of Products

7. Increasing Service Intensity of Goods and Services

These two principles are most applicable to manufacturing and services industries, sectors which directly "deliver" products and services to customers. Although it can be argued that reduced costs in the primary industry initiates a "domino effect" up the industrial ladder, where secondary and tertiary industries receive cheaper processed materials and goods, it is difficult to establish financial linkages. Specifically, in the nonferrous metals industry and most primary industries, which produce materials from raw minerals for manufacturers, no final "customer" product exists, and all contributions to extended durability and increased service intensity are indirect.

The sample eco-efficient framework devised in this study is summarized in Table 4.

Measuring Eco-Efficiency for Nonferrous Mining Firms and Other Businesses

The development of effective measurement strategies is an essential prerequisite to promoting any eco-efficiency framework in any business. This can be achieved through the creation of eco-efficient performance evaluation indices, which help a firm monitor and improve environmental performance. The particular method used to quantify and measure eco-efficiency in the nonferrous mining industry is a generic tool that can be used by all industrial sectors.

In the development of eco-efficiency principles, several stages exist. First, key goals should be identified. This includes identifying a financial return for each improvement in environmental efficiency (as per the 7 principles of eco-efficiency or whichever principles are applicable) and selecting a method to monitor productivity. Second, a measurement parameter should be assigned to each principle. For example, if the goal was "energy conservation," an appropriate measurement parameter would be "annual reduction in coal consumption." Third, corrective methods must exist for each principle, in case goals are not achieved. Using the same example of "energy conservation," in the event that the goal for annual reductions in coal use is not achieved, an appropriate corrective measure would be to conduct an energy audit.

According to the WBCSD, all eco-efficient principles should contain the following components: 1) a meaningful indication to improving the quality of life; 2) a decision-making tool; 3) recognition of the diversity of business; 4) a

Table 4. The Formulated Sample Framework of Eco-Efficiency for the Nonferrous Mining Sector

Reduced Material Intensity	Reduced Energy Intensity	Increased Recycl-ability	Reduced Toxic Dispersal	Renew-able Usage	Extended Product Durability	Increased Service Intensity
- Decrease water consumption - Reuse mine wastes - Install an EMS	- Reuse waste heat - Energy-efficient technologies - Use "waste" energies	- Improve treatment of AMD - Scrubbers - Improve handling of toxic agents	- Chemical recycling - Reprocess wastes	- Passive energies - Low sulphur coals - Renewable substitution	- N/A	- N/A

benchmarking or benchmarkable component; 5) clearly defined and measurable data; 6) a meaningful message to stakeholders; and 7) a holistic evaluation of the organization [15]. The challenge is developing appropriate environmental measurement parameters that can be measured against economic savings. Once this is accomplished, however, firms can effectively monitor their performance and benchmark against other firms in their respective industry.

CONCLUSION

The concept of eco-efficiency describes strategies that protect the environment and, at the same time, save a corporation money. The WBCSD has identified seven key principles of eco-efficiency, most of which can apply to any firm within any sector of industry. Efforts must begin in the primary sector, where raw materials are extracted and produced for manufacturing firms. In this particular study, the importance of eco-efficiency in the nonferrous metal mining industry was examined. Key environmental issues within the sector were discussed and a sample framework of eco-efficiency was developed. The widespread adoption of these and/or similar practices throughout the industry would lead to reduced impacts to the environment and help move the mining industry further toward sustainability.

REFERENCES

1. Z. Jeffries, The New Industrial Development and Exploitation of Metals and Alloys, in *Modern Uses of Nonferrous Metals,* American Institute of Mining and Metallurgical Engineers, 1935.
2. W. Hume-Rothery, *Electrons, Atoms, Metals and Alloys,* Dover Publications, New York, 1963.
3. H. C. Kazanas, *Properties and Uses of Ferrous and Nonferrous Metals,* Prakken Publications, Michigan, 1979.
4. UNEP, *Environmental Aspects of Selected Non-Ferrous Metals (Cu, Ni, Pb, Zn, Au) Ore Mining: A Technical Guide,* United Nations Environment Programme, Industry and Environment Programme Activity Centre, France, 1991.
5. E. Urquhart, *The Canadian Nonferrous Metals Industry: An Industrial Organization Study,* Centre For Resource Studies, Queen's University Press, Kingston, 1978.
6. W. Cragg, D. Pearson, and J. Cooney, Ethics, Surface Mining and the Environment. *Resources Policy, 21,* pp. 229-235, 1995.
7. M. Ruth, Thermodynamic Constraints on Optimal Depletion of Copper and Aluminum in the United States: A Dynamic Model of Substitution and Technical Change, *Ecological Economics, 15,* pp. 197-213, 1995.
8. WCED, *Our Common Future,* World Commission on Environment and Development, Oxford University Press, New York, 1987.
9. P. Crabbe, *Sustainable Development: Concepts, Measures, Market and Policy Failures at the Open Economy, Industry and Firm Levels,* Industry Canada, Occasional Paper Number 16, Ottawa, 1997.

10. L. D. DeSimone and F. Popoff, *Eco-Efficiency: The Business Link to Sustainable Development,* MIT Press, London, 1997.
11. S. Schmidheiny, *Changing Course, A Global Business Perspective on Development and the Environment,* MIT Press, Cambridge, 1992.
12. G. Wyburd, BCSD + WICE = WBCSD, *Business Strategy and the Environment, 5,* pp. 48-50, 1996.
13. WBCSD, *Annual Review 1996 (Annual Report),* World Business Council for Sustainable Development, Geneva, 1997.
14. B. Stigson, Business Progress Towards Sustainable Development, *Energy and Environment, 9,* pp. 141-145, 1998.
15. WBCSD, *Cleaner Production and Eco-Efficiency: Complementary Approaches to Sustainable Development,* World Business Council for Sustainable Development, Geneva, 1997.
16. S. Schmidheiny and F. Zorraquin, *Financing Change: The Financial Community, Eco-Efficiency, and Sustainable Development,* MIT Press, London, 1996.
17. WBCSD, *Eco-Efficient Leadership for Improved Economic and Environmental Performance,* World Business Council for Sustainable Development, Geneva, 1997.
18. P. Schrivistava, *Greening Business: Profiting the Corporation and the Environment,* Thomson Executive Press, Ohio, 1996.
19. S. W. Churchill, The Reduction of Air Pollution by Improved Combustion, *Energy Conversion and Management, 38,* pp. 1335-1341, 1997.
20. E. K. Silbergeld, The Hazards of Synthetic (Anthropogenic) Chemicals, *Toxicology Letters, 82-83,* pp. 835-841, 1995.
21. T. C. R. Van Someren, Sustainable Development and the Firm: Organizational Innovation and Environmental Strategy, *Business Strategy and the Environment, 4,* pp. 23-33, 1995.
22. R. U. Ayres, Metals Recycling: Economic and Environmental Implications, *Resources, Conservation and Recycling, 21,* pp. 145-173, 1997.
23. O. Kaarstad, Fossil Fuels and Responses to Global Warming, *Energy Conversion and Management, 36,* pp. 869-872, 1995.
24. A. J. DeRon, Sustainable Production: The Ultimate Result of a Continuous Improvement, *International Journal of Production Economics, 56-57,* pp. 99-110, 1998.
25. T. Nireki, Service Life Design, *Construction and Building Materials, 10,* pp. 403-406, 1996.
26. J. C. Van Weenen, Towards Sustainable Product Development, *Journal of Cleaner Production, 3,* pp. 95-100, 1995.
27. R. Meihkamp, Changing Consumer Behaviour Through Eco-Efficient Services: An Empirical Study of Car Sharing in the Netherlands, *Business Strategy and the Environment, 7,* pp. 234-244, 1998.
28. E. H. Rybicka, Impact on Mining and Metallurgical Industries on the Environment in Poland, *Applied Geochemistry, 11,* pp. 3-9, 1996.
29. I. Thornton, Impacts of Mining on the Environment; Some Local, Regional and Global Issues, *Applied Geochemistry, 11,* pp. 355-361, 1996.
30. C. Chukwuma, Sr., Environmental and Social Consequences of Metals and Mines on Water—A Viewpoint, *International Journal of Environmental Studies, 54,* pp. 73-81, 1998.

31. J. B. Mosher and L. Figueroa, Biological Oxidation of Cyanide: A Viable Treatment Option for the Minerals Processing Industry, *Minerals Engineering, 9,* pp. 573-581, 1996.
32. D. B. Porcella, C. Ramel, and A. Jernelov, Global Mercury Pollution and the Role of Gold Mining: An Overview, *Water, Air and Soil Pollution, 97,* pp. 205-207, 1997.
33. L. D. Lacerda, Global Mercury Emissions from Gold and Silver Mining, *Water, Air and Soil Pollution, 97,* pp. 209-221, 1997.
34. C. B. Gill, *Nonferrous Extractive Metallurgy,* John Wiley & Sons, New York, 1980.
35. M. A. Lusis, A. J. S. Tang, W. N. Chan, D. Yap, J. Kurtz, and P. K. Misra, Sudbury Smelter Impact on Atmospheric Deposition of Acidic Substances in Ontario, *Water, Air, and Soil Pollution, 30,* pp. 897-908, 1986.
36. M. Misra, K. Yang, and R. K. Mehta, Application of Fly Ash in the Agglomeration of Reactive Mine Tailings, *Journal of Hazardous Materials, 51,* pp. 181-192, 1996.
37. C. Herr and N. F. Gray, Sampling Riverine Sediments Impacted by Acid Mine Drainage: Problems and Solutions, *Environmental Geology, 29,* pp. 37-45, 1997.
38. B. Gazea, K. Adam, and A. Kontopoulos, A Review of Passive Systems for the Treatment of Acid Mine Drainage, *Minerals Engineering, 9,* pp. 23-42, 1996.
39. T. J. Nieman and Z. R. Merkin, Wildlife Management, Surface Mining, Regional Planning, *Growth and Change, 26,* pp. 405-424, 1995.
40. Y. S. Fangary, A. Ghani, A. S. El Haggar, and S. S. Williams, The Effect of Fine Particles on Slurry Transport Processes, *Minerals Engineering, 10,* pp. 427-439, 1997.
41. J. O. Leppinen, P. Salonsaari, and V. Palosaari, Flotation in Acid Mine Drainage Control: Benefaction of Concentrate, *Canadian Metallurgical Quarterly, 36,* pp. 225-230, 1997.
42. A. Kontopoulos, K. Komnitsas, A. Xenidis, and N. Papassiopi, Environmental Characterization of the Sulphidic Tailings in Lavrion, *Minerals Engineering, 8,* pp. 1209-1219, 1995.
43. K. M. Azizli, T. C. Yau, and J. Birrel, Design of the Lohan Tailings Dam, Mamut Copper Mining, Sdn.Bhd., Malaysia, *Minerals Engineering, 8,* pp. 705-712, 1995.
44. C. B. Gill, *Nonferrous Extractive Metallurgy,* John Wiley & Sons, New York, 1980.
45. A. Warhurst and G. Bridge, Improving Environmental Performance Through Innovation: Recent Trends in the Mining Industry, *Minerals Engineering, 9,* pp. 907-921, 1996.
46. R. G. Orr, W. J. Aldag, O. A. Laine, and W. T. Anderson, Recovery of Nickel from Waste Materials, in *Waste Processing and Recycling in Mining and Metallurgical Industries,* Canadian Institute of Mining, Metallurgy and Petroleum, Quebec, pp. 23-34, 1992.
47. C. T. H. Henda, ISO 14000 Audits and Legal Responsibility, *Environmental Technology, 7,* pp. 38-40, 1997.
48. R. E. Kohn, Exporting Toxic Waste, *Socio-Economic Planning Sciences, 29*:3, pp. 187-195, 1995.
49. J. M. Hollander and T. R. Schneider, Energy-Efficiency: Issues for the Decade, *Energy, 21,* pp. 273-287, 1996.
50. A. C. Sheldon, Energy Use and Conservation in Aluminum Production, in *Energy Use and Conservation in the Metals Industry,* Metallurgical Society of AIME, 1975.

51. M. M. C. Alkemade and J. I. A. Koene, The Useful Application of Sulphur-Bound Waste Materials, *Waste Management, 16,* pp. 185-188, 1996.
52. N. J. Sell, *Industrial Pollution Control: Issues and Techniques,* Van Nostrand Reinhold Press, New York, 1992.
53. B. Gazea, K. Adam, and A. Kontopoulos, A Review of Passive Systems for the Treatment of Acid Mine Drainage, *Minerals Engineering, 9,* pp. 23-42, 1996.
54. J. Weickowska, Catalytic and Adsorptive Desulphurization of Gases, *Catalysis Today, 24,* pp. 405-465, 1995.
55. J. B. Mosher and L. Figueroa, Biological Oxidation of Cyanide: A Viable Treatment Option for the Minerals Processing Industry? *Minerals Engineering, 9,* pp. 573-581, 1996.
56. L. Smith, J. Means, and E. Barth, *Recycling and Reuse of Industrial Wastes,* Battelle Press, Columbus, 1995.
57. K. H. Rao and K. S. E. Forssberg, Mixed Collector Systems in Flotation, *International Journal of Mineral Processing, 51,* pp. 67-79, 1997.
58. I. K. Wernick and N. J. Themelis, Recycling Metals for the Environment, *Annual Review on Energy and Environment, 23,* pp. 465-497, 1998.
59. A. K. Meier, Observed Energy Savings from Appliance Efficiency Standards, *Energy and Buildings, 26,* pp. 111-117, 1997.
60. J. S. Shih and H. C. Frey, Coal Blending Optimization under Uncertainty, *European Journal of Operational Research, 83,* pp. 452-465, 1995.
61. D. K. Sharma and S. K. Singh, Extraction of Assam Coal through Stepwise Alkali Treatment under Ambient Pressure Conditions, *Fuel Processing Technology, 45,* pp. 11-25, 1995.

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