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THE INDUSTRIAL ECOLOGY OF STEEL

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ABSTRACT

This study performs an integrated assessment of new technology adoption in the steel industry. New coke, iron, and steel production technologies are discussed and their economic and environmental characteristics are compared. Based upon detailed plant level data on cost and physical input-output relations by process, this study develops a simple mathematical optimization model of steel process choice. This model is then expanded to a life cycle context, accounting for environmental emissions generated during the production and transportation of energy and material inputs into steelmaking. This life-cycle optimization model provides a basis for evaluating the environmental impacts of existing and new iron and steel technologies. Five different plant configurations are examined from conventional integrated steel production to completely scrap-based operations. Two cost criteria are used to evaluate technology choice: private and social cost, with the latter including the environmental damages associated with emissions. While scrap based technologies clearly generate lower emissions in mass terms, their emissions of sulfur dioxide and nitrogen oxides are significantly higher. Using conventional damage cost estimates reported in the literature suggests that the social costs associated scrap-based steel production is slightly higher than integrated steel production. This suggests adopting a life-cycle viewpoint can substantially affect environmental assessment of new technologies. Finally, this study also examines the impacts of carbon taxes on steel production costs and technology choice.

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CHAPTER I. INTRODUCTION

The steel industry provides a classic example of an evolving industrial ecosystem. During the late 19th and early 20th century, integrated steel plants in Pittsburgh and Chicago provided neighboring communities with coke oven gas for lighting and district heating. Today, these same plants recycle off-gases to generate steam and electricity within the plant. By-product coke ovens were also a major source of petrochemicals during this era before modern petroleum refining became prevalent. Post consumer recycling is also important with roughly 50 percent of all steel in the U.S. coming from recycled scrap steel. Like the Kalundborg case discussed by Ehrenfeld and Gertler (1997), these loop-closing activities slowly developed over time as firms identified and characterized waste sources and sinks. Steel companies in the U.S. followed a similar course but were driven more by intense competition from producers both home and abroad.

Technological innovations have always been important in steelmaking (Barnett and Crandall, 1986). Steel mills use one of two types of furnaces to make new steel. Both furnaces recycle old steel into new, but each is used to create different products for varied applications. The first, the basic oxygen furnace (BOF), uses about 28 percent steel scrap to make new steel. The other 72 percent is molten iron produced from blast furnaces, which require iron ore from mines, limestone from quarries, and coke from batteries of ovens. The BOF furnace produces uniform and high quality flat-rolled steel products used in cans, appliances, and automobiles. The other type of steelmaking furnace, the electric arc furnace, melts virtually 100 percent steel scrap to make new steel. Steel minimills using these furnaces now produce nearly 50 percent of total U.S. steel production. This steel is used primarily to make products that have long shapes, such as steel plates, rebars and structural beams. Steel minimills are far less capital intensive than integrated mills because they do not require blast furnaces and coke ovens. Their reliance on steel scrap also affords them an environmental advantage in lower energy and virgin material consumption.

Minimills have entered the last domain of integrated steel, employing thin slab casting that can yield relatively high quality sheet steel. This additional competitive force comes at a time when many integrated steel firms are seriously reevaluating their plants in light of the recent regulations controlling toxic emissions from coke ovens. Most existing methods of producing coke generate fugitive emissions that contain potentially carcinogenic substances, such as benzene soluble organics (BSOs). A variety of strategies, some entailing additional investment and/or higher operating costs, can reduce these emissions. Considine, Davis, and Marakovits (1992) conducted a study estimating the benefits and costs of coke oven regulations, incorporating closure decisions and new technology adoption, and found that investment in new coking technologies is profitable under the new regulations.

In fact, Inland Steel is currently building a large battery of coke ovens using the Thompson non-recovery process, heralded as a possible clean technology breakthrough. This design allows the controlled burning of coal that destroys the Benzene Soluble Organics (BSOs) and other potentially carcinogenic compounds contained in the offgases of the coking process. There are, however, relatively large amounts of sulfur dioxide emissions from the waste heat, which can be recovered via heat exchangers and used to produce steam for electricity generation.

There are several other new iron and steelmaking technologies that could either substantially reduce or eliminate coking coal consumption in the production of steel. Pulverized coal injection (PCI), replacing up to 40 percent of the coke needed in ironmaking, is widely used in Europe, Asia, and Japan and is now gaining favor in the United States (McManus 1992a). Natural gas injection is a similar technology being promoted by the Gas Research Institute (Brooks 1992).

There are also three new steelmaking technologies that could totally eliminate the need for coke. First, there is direct reduction (DR), a coal or natural gas-based ironmaking process, that produces an iron substitute for scrap in electric arc furnaces. Another coke eliminating option is the Corex process, which does not require coke and produces a large volume of waste heat that can be used to cogenerate electricity. Finally, there is direct steelmaking (DSM), a process that could eliminate the need for coking and ironmaking in traditional integrated steel mills. Unlike PCI, DR, and COREX, this technology is currently not under commercial development.

This study presents an integrated assessment of these technological options. Our analysis is based upon an engineering-economic model of steel production with environmental emissions coefficients from a life cycle assessment (LCA) of steel production from primary resource extraction to the plant gate. Our model selects the optimal combination of activities to minimize cost subject to a number of constraints, including mass and energy balances for intermediate products. Substitute activities represent new technologies available for possible adoption. Unlike many aggregate process models, our model is for a specific steel plant with coefficients based upon actual operating performance.

The analysis presented below uses this model in three ways. The first application compares the economic and environmental performance of steel technologies, ensuring technical feasibility. This analysis provides insights into the tradeoffs between cost and environmental objectives, such as reducing greenhouse gas emissions, toxic discharges, and acidic residuals. The second application solves the model under two different definitions of cost: private and social. The latter includes private costs and the environmental damages associated with the LCA impacts. This allows us to determine whether steel production technology would be different if environmental externalities were internalized through a system of taxes or permits. Finally, we examine the impact of carbon taxes on technology choice in the steel industry.

The next chapter discusses recent technological development in the steel industry. A discussion of factors affecting emissions appears in Chapter III. A comparison of the resource and environmental characteristics of alternative steel production paths appears in Chapter IV. The development of the economic-engineering process model with life-cycle impacts is in Chapter V. This model is then used in Chapter VI to compare the cost and environmental emissions for technically feasible plant configurations using these technologies. The final chapter summarizes our main points and discusses the policy implications of this research.

CHAPTER II. NEW TECHNOLOGY IN THE STEEL INDUSTRY

Competition and recent environmental regulations are inducing technological innovations that will transform metal refining and smelting. The steel industry has been evolving from a highly capital intensive, batch processing production technologies to less capital intensive, continuous processing systems that are cleaner and more energy efficient. There are many indications suggesting that this transformation is accelerating. Moreover, faced with ever more stringent environmental controls, many firms are redesigning their production process to eliminate pollution or to utilize wastes as resources. This strategy is gaining hold in many industries and is likely to become more widespread as firms learn that reducing pollution in some cases may lower energy and material costs. Investments in new technology often hold the key to these cost savings. Understanding the key characteristics of these technologies and their prospects for commercial development is the primary objective of this chapter.

We begin our discussion by providing an overview of the production process to establish a context for our discussion of new iron and steel production technologies. With the recent large capacity additions by steel minimill companies in flat rolled sheet production, there is increasing concern about the availability of iron bearing raw materials. As a result, new ironmaking technologies, iron waste recovery systems, and steel scrap purification techniques are under development that could potentially offer steelmakers more flexibility in their raw material choices. Further down the production line, the success of thin slab casting appears to be ushering in developing strip-casting technologies.

The distinction between integrated plants and steel minimills is beginning to blur. Most steel plants in the United States are either traditional ore based integrated plants producing high quality sheet and strip products or traditional scrap based electric arc furnace (EAF) plants producing bars, wire, structural shapes, and other long products. These polar opposites appear in Figure 1. Note the difference in scale and the greater number of steps involved with integrated steel production. Recently, some hybrid plant designs are emerging. Perhaps the best example is the Nucor plant in Crawfordsville, Indiana that produces sheet products using a thin slab caster fed by steel produced in EAFs using a mixture of scrap and iron carbide, a new ferrous material input. This plant configuration appears in the third section of Figure 1. Another variation involves integrated firms adopting minimill steel technologies, such as direct ironmaking, advanced EAFs, and thin slab casting, a configuration known as mini-integrated (see section 2 of Figure 1). The concern over the availability of high quality iron material inputs appears to be main impetus for these innovations. Energy costs, capital availability, transportation costs, and access to product markets are additional considerations. While there may be no unique optimal mill configuration, the trend is toward so-called market mills that supply a market niche within a geographical area.

New technology adoption continues across all plant types. Integrated mills continue to modernize across the entire production process from cokemaking to rolling and finishing operations. For instance, Inland Steel constructed non-recovery coke ovens and most integrated firms in the US are substantially raising their rates of pulverized coal injection into blast furnaces. Minimills continue to advance electric arc furnace technology. There is a growing list

of new ironmaking technologies designed to provide a substitute for high quality scrap, which is in greater demand since minimills are employing new casting technologies to produce high quality products for appliance and automotive markets. Innovations in electric arc furnaces, such as oxygen injection, are matching this new flexibility in raw material supply. These innovations are discussed in the following sections.

Figure 1: Future steel plant configurations

PCI — Pulverized coal injection

EAOF — Electric arc oxygen furnace

New OSM—Conventional or continuous refining with scrap preheating

Advanced Melter — Fossil fuel or hybrid melter with scrap preheating

Source: (Freuhan, R.J., et. al., 1995)

COKEMAKING

Coke is a basic material used to manufacture iron in the steel industry. Iron naturally occurs in oxide ores, and a chemical reaction called reduction is necessary to remove the oxygen, leaving the iron in metallic form. Carbon bonds strongly with oxygen, and coke, the residual char after heat forces the organic volatile matter from coal, is composed primarily of fixed carbon. In the blast furnace, the carbon from coke reduces iron ores into molten iron or pig iron. Subsequently, controlled oxidation forces added oxygen to react with large amounts of excess carbon, leaving an iron product with about 1% carbon—steel.

Since the nineteenth century, the steel industry has been manufacturing coke in by-product recovery ovens, designed to capture the volatile matter driven from coal during coking. When cooled, the by-product matter condenses into coal tar, a source of many chemical products such as synthetic tars, plastics, and crude light oil.

Operators of by-product recovery coke oven batteries are contending with several market forces and regulatory issues. One-fifth of the coke oven batteries in the United States are operating well beyond their expected productive life of thirty to thirty-five years (Peters 1992, p. 18). Emissions from by-product recovery coke ovens contain several carcinogenic compounds such as benzene soluble organics (BSO), which affect public health. The Clean Air Act Amendments (CAAA) of 1990 specify minimum emission limits, Maximum Available Control Technology (MACT) and the more stringent Lowest Achievable Emission Rate (LAER), intended to reduce air toxic emissions by 90% by 2003. If residual emissions do not provide an "ample margin of safety" to protect the most exposed individual, EPA will promulgate even more stringent controls on coke oven emissions.

In a study of the impacts of the CAAA's coke oven emission controls on the United States steel industry, Considine, Davis, and Marakovits (1993a) use an engineering-economic approach to measure the economic consequences of regulation and its effect on technology adoption in the steel industry. In a later, preliminary study estimating the costs and benefits of coke oven emission controls, they incorporate uncertainty surrounding key parameters, such as EPA's controversial estimate of unit risk, the probability of developing cancer from exposure to one unit of coke oven emissions (Considine and Marakovits 1993). They assign probability distributions for eight parameters and generate one hundred random experiments to perform a stochastic analysis. As in the earlier study, the authors impose MACT and LAER coke oven emission limits on the steel industry in 1995 and 1998, respectively, and compare the results with the base year solutions to estimate the industry costs due to regulation.

In the earlier analysis, Considine et al. conclude that coke oven emission controls would accelerate the current trend towards electric arc steelmaking and nonpolluting coking technologies (Considine et al. 1993a, pp. 452-3). However, lengthy plant construction lead times would create coke shortages, causing imports to rise. The older coke batteries shut down under MACT, but newer, low cost batteries shut down in 1998 for exceeding LAER emission limits.

Steel producers have continually adopted innovative steelmaking technologies. Aging coke oven batteries and declining coking capacities over time have been forcing integrated producers to examine alternatives to traditional coking and ironmaking practices (Davis and Considine 1992, p. 57). In addition, environmental regulations on coke oven emissions may stimulate technological innovation though regulators intend the MACT standard to encourage increased use of proven technologies (Graham and Holtgrave 1990, pp. 243-4). However, environmental regulations raise the costs of coke production. For example, only twelve percent of the batteries existing in 1991 can economically achieve the less stringent MACT emission limits, and 83% of those batteries require rebuilding (Peters 1992, p. 15). As a result, environmental controls could accelerate the steel industry's "natural" rate of technology adoption towards processes that reduce or even eliminate coke requirements.

The steel industry has several technological choices to reduce coke oven emissions. The viability of each option varies by coke plant based on the age and condition of the batteries, existing coke oven emission levels, availability of capital, plant location, and relative material and energy prices, among others. In addition to importing foreign coke, steel producers can retrofit or rebuild existing coke ovens, as well as install new wet-coking batteries (Considine et al. 1993a, p. 445). Retrofitting involves replacing the coke ovens doors and their jambs. New jambs may necessitate replacement of the refractory bricks, depending on the condition of the oven walls (Struthers Corporation 1991, p. 14). A pad-up rebuild involves demolishing the existing battery to the concrete "pad" or foundation and building a new battery of the same dimensions in its place (Struthers Corporation 1991, p. 15).

Besides additional investment in the wet-coking technology, steel producers have several new processes to consider, which we describe below. Coke producers can invest in nonpolluting coking technology called Jewell. Alternatively, the industry can adopt iron and steelmaking processes, such as pulverized coal injection, direct reduction, and scrap-based steelmaking, which save or eliminate coke altogether. Finally, if coke producers cannot economically control coke oven emissions to regulation levels, they can cease operations.

Nonpolluting Coking of Coal

CAAA require the administrator of EPA to evaluate the Jewell-Thompson oven, a nonpolluting coke oven presently being used in Vansant, Virginia by Jewell Coal and Coke Company, owned by Sun Coal Company. Ironically, the Jewell-Thompson technology is similar to the obsolete beehive oven used in mid-eighteenth century. Unlike the slot-type wet-coking oven, the Jewell oven operates on negative pressure, which minimizes fugitive emissions because coal tars and gas combust inside the oven and flues (Knoezner et al. 1992, p. 50). Therefore, this process recovers no by-products, eliminating the need for by-product recovery facilities and the disposal of hazardous wastes. Provisions for the recovery of excess heat will permit cogeneration of electricity (Knoezner et al. 1992, p. 50).

A Jewell oven is about twelve feet wide and forty-five feet long, accommodating a coal charge of twenty-five to fifty tons (Knoezner et al. 1992, p. 50). Oven charging is by a conveyor machine through the pusher side door and not from above (Knoezner et al. 1992, p. 52). The operator admits a limited amount of air into the oven to combust some of the volatile matter being driven from the coal, which generates heat required for coking. The partially combusted gas escapes through sole flues located below the oven floor, combusting further within the flues and creating additional heat underneath the coal bed (Knoezner et al. 1992, p. 51). Coking time can range between twenty-four to forty-eight hours (Knoezner et al. 1992, p. 50). Pushing and quenching operations are similar to the wet-coking process (Knoezner et al. 1992, p. 52).

Other no-recovery coke oven designs include the European Jumbo Coking Reactor and the American Calderon coking process currently under development may completely eliminate all coke-oven emissions (Wrona, 1997, p. 60). Dry quenching is another technique to reduce emissions, recovering heat from the hot coke during quenching to generate steam. This process, however, uses more electricity than other coking processes and requires greater inputs of coking coal. Another process is form coking that produces briquettes by drying and partially oxidizing

lower quality noncoking pulverized coal with steam in a fluidized-bed reactor, followed by carbonization at higher temperatures (Lankford, et. al, 1985, p. 142). Both of these processes offer a relatively environmentally acceptable means of producing coke and are extensively used in Japan and Russia but have yet to find extensive use in North America.

Aging cokemaking facilities, stringent emission controls on coke oven emissions, and perhaps increased scarcity of metallurgical coal in some areas have forced plant operators to examine alternatives to traditional iron and steelmaking (Davis and Considine 1992, p. 57). Below we discuss several new technologies that lower coke requirements or eliminate the need for coke.

Pulverized Coal Injection

Pulverized coal injection (PCI) and continuous casting reduce the need for metallurgical coke. To reduce iron ore to its metallic form suitable for production, iron makers can inject pulverized coal into a blast furnace proper to lower coke requirements (Davis and Considine 1992, p. 57). One pound of pulverized coal can replace one pound of coke as a fuel and as a reducing agent (Unsworth et al. 1989, p. 1-20). Because pulverized coal cannot substitute for the permeability of porous coke or support the blast furnace burden, it cannot completely replace coke.

The U.S. Department of Energy's Clean Coal Technology Program is a coal injection project at Bethlehem Steel Corporation's Burns Harbor plant in northwest Indiana. The technology uses crushed coal as part of the fuel to fire blast furnaces, replacing natural gas or oil used in many plants today. In the process, both granulated and pulverized coal is injected into the blast furnace in place of natural gas (or oil) as a blast furnace fuel supplement. Emissions generated by the blast furnace itself remain virtually unchanged by the injected coal; the gas exiting the blast furnace is clean, containing no measurable SO₂ or NO_x. Sulfur from the coal is removed by the limestone flux and bound up in the slag, which is a marketable by-product. In addition to the net emission reduction realized by coke displacement, high temperatures increase blast furnace production. Coal injection also allows the use of a wide range of relatively inexpensive coals, in contrast to coke, which can only be made from certain high quality coals.

Two high-capacity blast furnaces at the Burns Harbor plant, each with a production capacity of 7,000 net tons per day of hot metal, have been retrofitted with the coal injection technology. The two units will use about 2,800 tons/day of coal during full operation, replacing about 40% of the coke needed in the furnaces. Bituminous coals with sulfur content ranging from 0.8% to 2.8% from West Virginia, Pennsylvania, Illinois, and Kentucky are to be used. A western sub-bituminous coal having 0.4-0.9% sulfur might be tested also.

Construction was completed in February 1995. Bethlehem Steel submitted a public design report in March 1995. Start-up testing has been completed, and the plant is complete. Operational testing began in November 1995. Furnace C has been operated with an average coal injection rate of 275 lbs/net ton of hot metal, using low-volatile bituminous coals. Bethlehem Steel has determined that this injection rate will be the new operating baseline for Furnace C for all future test coal comparisons. Furnace C also has been operated with a coke rate of approximately 650 lbs/net ton of hot metal without coal injections, down from 770 lbs/net ton.

Furnace D has been operated with a coal injection rate of approximately 190 lbs/net ton of hot metal, which is above its design point of 180 lbs/net ton. Bethlehem Steel has completed repairs to a coal preparation plant necessitated by tramp organics in recent coal supplies. Bethlehem Steel plans to increase substantially the coal feed rate through all 52 tuyeres for comparison with the baseline standard of 275 lbs/net ton of hot metal on Furnace C.

The granular coal injection project at Bethlehem Steel's Burns Harbor plant in Northern Indiana offers the U.S. steel industry a way to become more competitive while improving its environmental performance. The technology can be applied to essentially all U.S. blast furnaces. It should be applicable to any rank coal commercially available in the United States that has a moisture content no higher than 12%. The environmental impacts of commercial application come primarily from a reduction in the need for coke, the production of which can release emissions of sulfur dioxide and air toxics. Also, because a wide range of relatively low-cost coals can be used to replace processed coke, the ironmaking process is less expensive. The cost of more expensive fuels such as natural gas and oil can be avoided.

Other alternatives eliminate the need for coke. These processes, discussed below, include direct reduction and scrap-based steelmaking. Alternatively, steel makers can also import semi-finished steel slabs that eliminate both coking and ironmaking operations (Considine et al. 1993a, p. 445).

DIRECT REDUCTION

Technically speaking, the direct reduction process produces iron known as directly reduced iron (DRI) by reducing iron ore below the melting point of the manufactured iron (U. S. Steel 1985, p. 507). This process simply reduces iron ore into a form suitable for steelmaking without using coke. Blast furnaces, basic oxygen furnaces, and electric arc furnaces can use DRI (MIDREX 1993). In fact, DRI is a substitute for high quality scrap in an electric arc furnace (EAF), discussed below (Hess 1992, p. 26).

Direct reduction can either be gas-based or coal-based (Davis and Considine 1992, p. 57). Gas based direct reduction processes currently dominant world production, although there are several promising coal-based direct reduction technologies. Most DRI processes produce with a shaft furnace, although newer designs incorporate fluidized bed reactors.

Gas-Based Direct Reduction

Gas-based direct reduction produces directly reduced iron. Although DRI production has wide applications in developing countries like Mexico, until recently the United States and Canada have shown little interest in adopting natural gas-based direct reduction for several reasons (Hess 1992, p. 26). Liquid natural gas (LNG) and naphtha, as well as coke oven gas, by-product gas, and coal gas, can be used as an energy source, but natural gas is the preferred reducing agent in direct reduction (Hess 1992, p. 26; MIDREX 1993). In North America, relatively high natural gas prices have hindered widespread practice of gas-based direct reduction. Also, DRI is a substitute for high quality scrap, but quality scrap is readily available at low cost (Hess 1992, p. 26). High capital costs of \$400 per annual ton of installed gas-based

direct reduction capacity may not be justified for an average steelmaking facility (Hess 1992, p. 27). Finally, operators of EAFs claim that they need additional energy to melt DRI, which may contain between 2.8 to 7% of gangue, an undesirable nonmetallurgical material (Hess 1992, p. 26; MIDREX 1993).

Midrex

The Midrex process is currently the dominant gas-based direct reduction process in the world, accounting for 65 percent of the 27.4 million metric tons of DRI production around the world in 1994. Their process converts iron oxide from either 100% lump ore, 100% pellets shaped from iron ore fines, or some combination into low residual, "prereduced iron units" at low pressure (Hess 1992, p. 26; MIDREX 1993). The process may use additional iron oxide fines to maximize the yield but not to replace the lump ore or pellets (MIDREX 1993).

Iron oxide is fed into a vertical vessel called a shaft furnace from above and passes through two independent zones. The iron oxide is heated and reduced in the upper reduction zone by hot reducing gas containing hydrogen and carbon monoxide. In the lower cooling zone, gas cools the reduced iron to increase the carbon content. The shaft furnace discharges the DRI from below. The DRI can be shaped into lumps or pellets or be compacted into uniform briquettes called hot briquetted iron (HBI) (MIDREX 1993).

The hot reducing gas is a combination of natural gas and recycled gas from the shaft furnace. The mixing of gas occurs in a gas-tight reformer, a refractory-lined furnace containing alloy catalyst tubes. As heated gas flows upward through the tubes, it reforms into reducing gas. To improve thermal efficiency, a heat recovery system can preheat both the gas mixture flowing through the catalyst tubes and the air used for combustion in the reformer by capturing the sensible heat generated from the reformer flues (MIDREX 1993).

HYL

The HYL I and HYL III processes account for 25.6 percent of world DRI production in 1994. These processes were developed more than two decades ago by HYL Technology Division of Mexico's Hylsa, S.A. de C.V. HYL offers three product options: traditional DRI (cold product in pellet or lump form), HBI (hot briquetted iron), HYTEMP Iron (hot product, pneumatically transported to the EAF). For each product option, the metallization and carbon can be varied according to the client requirements.

HYL is currently working on coupling a Corex plant (see below) and a HYL III plant using the off-gas from the former as a reducing gas for the latter. They are also improving their energy recovery systems, producing high pressure steam for electricity generation in a high-efficiency turbogenerator. This process allowing the DRI plant to be self-sufficient in electricity. They are also developing high-carbon DRI and Hytemp iron.

Arex

This DRI process is relatively new and was developed by Venezuela's Sidor (C.V.G. Siderurgica del Orinoco). Arex involves auto-reforming a mixture of natural gas and recycled top gas in a shaft furnace in the presence of hot iron, which acts as a catalyst to generate the gas

required for reducing iron oxide feed. In early 1995, this technology was retrofitted onto two Midrex HBI modules at India's Essar Steel Gujarat Ltd.. They are also working on applying this process to produce iron carbide for a continuous steelmaking operation. Reduced capital costs, environmental cleanliness, and the flexibility to use a variety of fuels and different ore and pellet types are some potential advantages of this process.

Iron Carbide

The iron carbide process is another gas-based direct reduction technology commercialized by Nucor at a plant site in Trinidad. This process uses natural gas and hydrogen reformed from methane as reductants, exposing iron ore fines to the gas for 10 to 14 hours in a fluidized bed operating at about 1,100° F. Iron carbide's reliance on relatively plentiful iron ore fines and its ability to easily dissolve in steel (some likened it to sugar dissolving in coffee) are two important advantages. Perhaps more importantly, iron carbide is pyrophoric, capable of igniting spontaneously in air. Nucor recently formed a joint venture with USX Corporation and Praxair Inc. to take advantage of this unique property with a feasibility study to determine the possibility to produce steel directly, using only iron carbide and oxygen, which would reap considerable energy savings and environmental benefits.

Iron carbide technology, however, has encountered some serious technical problems. The Trinidad plant was plagued with start-up problems, primarily with the material handling operation. Apparently, these problems were substantially resolved in 1996 as production reached 126,000 metric tons. A much more fundamental problem recently has been identified. Burlingame (1997, p. 1) recently noted the very low rate of reduction achieved thus far. Iverson from Nucor concurs, citing that their yield is currently 80 percent iron carbide and that they are installing additional hydrogen-generating equipment to increase this yield to 90 percent. Iverson is pessimistic about achieving consistently higher yields. Burlingame even suggested that Nucor consider abandoning iron carbide and converting the Trinidad plant to conventional DRI or HBI. This exchange suggests that low product yield may be a fundamental problem with iron carbide. This deficiency must be balanced with the main advantage of iron carbide in providing a source of energy in the EAFs. Despite these potential advantages, low prices for scrap, the main substitute for DRI, forced closure of the Trinidad plant in 1999.

Circofer & Circored

These are new coal and gas-based direct iron reduction processes designed by Lurgi, pioneer of the SL/RN Process, which produced about 1 million metric tons of DRI or slightly less than 4 percent of world production. Both processes use a combination of a circulating fluidized-bed (CFB) reactor and fluidized-bed (FB) technology in which pre-heated fine ore is pre-reduced to a 70% metallization degree and then reduced in a FB to a 93% metallization. Lurgi estimates the operating and capital costs for a Circored (gas) 500,000 tpy facility in Venezuela would be \$40 per ton for DRI and \$67.20 per tone for HBI (Isenberg-O'Loughlin, 1995, p. 39). Their Circofer design based on coal is designed for high cost gas areas, like the US. They estimate operating and capital costs for a 450,000 Circofer plant in the US of \$71.80 per ton for DRI and \$100.60 per ton for HBI.

Coal-Based Direct Reduction

By gasifying coal to produce reducing gas, iron makers can use coal-based direct reduction to produce hot liquid iron. These technologies offer considerable potential in many parts of the US where coal prices are on average about 60 percent of natural gas prices on a heat equivalent basis.

Corex

Corex is an alternative to gas-based direct reduction. Jointly developed by Voest-Alpine Industrieranlagenbau (VAI) and Deutsche Voest-Alpine Industrieranlagenbau (DVAI), developed the technology in the late 1970s and the process debuted in 1982. The Corex C-1000 plant module with 300,000 metric tons of installed capacity has been operating since 1989 at Iscor's Pretoria Works in South Africa, where noncoking coals are abundant, proving the technology on a small scale (McAloon 1990, p. 25 and Isenberg-O'Loughlin 1995, p. 40).

Corex uses two reactors to produce hot metal. A combination smelter/gasifier, a fluidized bed, generates the reducing gas from coal. The reactor, injected with noncoking coal and oxygen, partially oxidizes the coal, creating carbon dioxide, which reacts with the free carbon to create carbon monoxide (McAloon 1990, p. 28). A high temperature inside the reactor fosters the generation of high quality reducing gas from the gasifier mixture. A coolant gas lowers the temperature of the gasifier mixture after it exits the first reactor and before it enters a second reactor above it, the shaft furnace. Iron ore in either lump or pellet form charged into the shaft furnace reacts with the reducing gas, and liquid iron results (Delpont 1992, p. 185; McAloon 1990, p. 28).

Corex has several attractive features. Separate reactors for reduction and smelting allow greater process control (Delpont 1991, p. 189). For example, an operator can take a sample of the DRI from the reduction step rather than from the blast furnace. Further, this feature of separate reactors allows accommodation of a wide range of coals (McAloon 1990, p. 27). Also, besides producing hot metal, the Corex process generates hot gas that can be used as fuel in other steelmaking activities. The reaction in the shaft furnace is exothermic, generating hot off-gas. After being cleaned and cooled in a scrubber, the gas can be sold or used elsewhere in the facility (McAloon 1990, p. 28). Despite its attractive features, Corex uses oxygen, which is very expensive (McAloon 1990, p. 28).

Posco in South Korea was scheduled to start their C-2000 plant at the Pohang Works. This unit is designed for annual production of 660,000 short tons per year (stpy) of hot metal on a lump ore basis and 880,000 stpy on a pellet basis. Corex units are also under development by Hanbo Steel in Korea and the Jindal Group in India (Isenberg-O'Loughlin 1995, p. 40). There are also plans to offer a C-3000 module with annual capacity of 1.1 million stpy.

In the United States, the US Department of Energy announced on August 19, 1996, that it had completed negotiations with the CPICOR Management Company, L.L.C. to demonstrate direct ironmaking with an environmentally clean process for co-producing electricity. The project will be located at the Geneva Steel plant in Vineyard, UT. Construction of the project is projected to begin in April 1998 for completion in September 2000. The plant will be operated as

a demonstration through 2003. The energy efficiency of the CPICOR technology is much greater than competing commercial technology. This efficiency advantage is gained by more effective use of both the sensible heat in the process and the volatile matter in the coal, as well as by incorporation of the combined-cycle power generation system. The CPICOR project was originally proposed for an LTV Steel plant in Cleveland. When LTV later withdrew, Geneva Steel agreed to replace LTV as a project team member and to host the CPICOR project in Vineyard, Utah.

HIs melt

Presently in development stages, the HIs melt process is another coal-based direct reduction method to produce hot metal under a joint venture with CRA Ltd. and Midrex Corp. Located in Kwinana, Western Australia, the HIs melt Research and Development Facility scheduled testing and evaluation of the new technology for July 1993 (HIs melt 1993).

The HIs melt process produces hot liquid metal in a high intensity environment by injecting noncoking coal and iron ore fines into a molten iron bath (Prideaux 1993, p. 4). High intensity requires rapid conversion of the ore feed to liquid metal to minimize levels of slag, which can reduce iron yields (Hardie et al. 1993, p. 4). Use of iron ore fines eliminates the need for pelletization and may be an attractive feature to iron producers located in areas with limited lump ore resources.

Earlier HIs melt designs included a horizontal vessel. Coal is injected from below into a turbulent iron bath in the reduction vessel. The carbon from the coal dissolves in the molten bath and reacts with the oxygen from iron ore fed from above, leaving carbon monoxide and reduced iron (Prideaux 1993, p. 5). Unlike the Corex process, the reduction reactions are endothermic, i.e. absorb heat. To maintain the reactions, the carbon monoxide in the bath reacts with the oxygen from a hot air blast injected from above, generating heat. The hot air blast reduces the need for expensive oxygen. The high injection of coal from below generates bath turbulence, which is necessary to maintain a fountain of metal and slag droplets above the bath. The droplets absorb the heat from the carbon monoxide/oxygen reaction and return heat to the bath. Relatively hot gases exit the vessel and can be used to preheat and pre-reduce the iron ore feed (HIs melt 1993; Prideaux 1993, p. 5).

Early next year the researchers will replace the present horizontal reaction chamber with a new vertical vessel to simplify the operation of the process, and enable it to be scaled up to commercial size. If HIs melt's new vertical configuration proves to be effective, Hamersley Iron, an RTZ-CRA subsidiary, has already expressed interest in the possibility of constructing a HIs melt plant to produce up to two million tonnes of iron annually. Given the \$200 million cost of the 100,000 tonne pilot plant that represents an investment in the billion dollar range.

AIISI-DOE Direct Steelmaking

The AIISI-DOE (Aukrust, 1994) direct steelmaking project started in 1988 and ended in early 1994. The process entailed smelting iron ore pellets in a foamy slag created by the reaction of char from coal with molten slag to produce carbon monoxide, CO. The CO is post-combusted with oxygen, producing the heat necessary to sustain iron reduction. The uncombusted CO and

hydrogen from the coal are used to preheat and pre-reduce the iron pellets. This research program ended without solving all the problems associated with high volatile coals stemming from the design of the charging system and the low pressure of the operation. This project was followed with a study of the feasibility of converting steel plant wastes to pig iron. Currently waste is typically disposed of in landfills at continuously escalating costs. This process was demonstrated using the in-bath smelting pilot plant at Universal, Pennsylvania.

DIOS

The Direct Iron Ore Smelting (DIOS) process is under development by the Japan Iron and Steel Federation. A 21 ton per hour pilot plant was completed at NKK's Kelhin Works in late 1993. This plant is comprised of two two-stage furnaces for preheating and pre-reduction, which are both fluid beds. The results thus far appear successful, although commercialization appears sometime away. The technology appears to accept iron ore fines and to allow injection of fine coal via a gas-reforming system.

Fastmet

In this process, a combination of pulverized coal and iron ore fines are made into pellets. The pellets are fed into a doughnut-shaped rotary hearth furnace and heated. At 1,350 degrees Celsius, the pellets are reduced in 8-10 minutes. Under high heat, the pulverized coal serves as the reductant and burns off the oxygen in the iron ore. DRI can be charged hot to an adjacent melting furnace or briquetted for merchant shipment. Kobe Steel, Ltd. and Midrex Direct Reduction Corporation recently announced that they have discovered a refinement of this process under higher temperatures so that iron ore is reduced in a short 6 to 10 minutes.

Kobe Steel and Midrex plan to conduct research on the new molten ironmaking process in three stages. In Phase 1, running from July 1996 to March 1997, roughly 200 million yen will be invested to study the reaction mechanism and the basic technology of the process. In Phase 2, October 1996 to June 1998, the two companies plan to conduct bench-scale testing, investing some 500 million yen. Should the results of the first two phases be promising, the project will move into Phase 3, where potential process users will be invited to invest in the construction and operation of a pilot plant.

Finmet

Finos Metalizados translates to Metalized Fines, is a direct reduction process that utilizes iron ore fines to obtain a highly metallized product. This technology, patented by Fior de Venezuela (a subsidiary of Sidetur and CVG Ferrominera Orinoco) and the Austrian company Voest Alpine Industrieanlagenbau, (VAI), is based on a proved fluidized iron ore reduction process which produces a high quality briquetted product (HBI) at a low cost, which is easier to handle and transport, and does not require lump ore and pellets as feedstock. This is the main advantage of the FINMET process since fines are abundant in most of the iron ore mines worldwide, are less expensive, and do not require previous treatment such as for pellets. In addition, FINMET can produce briquettes with carbon content according to the customers requirements. Presently Fior de Venezuela is the only commercial plant in the world that processes natural iron ore fines in fluid beds for the production of briquettes. Fior is the pioneer of hot briquetting technology and its product is recognized worldwide for its excellent quality.

In September 1995, the Australian company The Broken Hill Proprietary (BHP) signed a letter of intent with Siderúrgica Venezolana SIVENSA and CVG Ferrominera Orinoco FMO, shareholders of Fior de Venezuela, to invest US\$700 million in the construction of a FINMET facility. The plant will consist of two modules and four battery/trains of reactors each with 500,000 metric tons per year of capacity each, for a total of 2 million metric tons per year. The new plant is called Orinoco Iron C.A. The plant construction was initiated in mid 1996 and the start up is projected for the third quarter of 1998. It will be operating at full capacity by 1999. The plant is being constructed in Puerto Ordaz, Venezuela. In addition, BHP decided to use the Finmet technology for its news plant in Port Hedland, Australia. This project will require an investment of US\$900 million. Its construction started at the end of 1995, and startup is scheduled for December 1997.

OXYGEN STEELMAKING AND REFINING

The basic oxygen furnace (BOF) converts iron into liquid steel, an iron product of about 1% carbon, as added oxygen reacts with any excess carbon. Although this steel furnace primarily uses hot metal as the primary feed, scrap can comprise up to 33% of the charge (Barnett and Crandall 1986, p. 3). The capacity of a BOF vessel is 200 to 300 tons (Barnett and Crandall 1986, p. 5). Unlike the coke ovens and blast furnace, there are no ready alternatives to the BOF other than scrap based steel production using electric arc furnaces. Nevertheless, incentives for innovation remain because the BOF process is capital intensive and inflexible with respect to scrap charge. In addition, charging and tapping BOFs together take twice as much time as steelmaking, reducing potential production and raising unit costs.

The American Iron and Steel Institute (AISI) Direct Steelmaking project examined alternatives to conventional oxygen steelmaking. Two processes appear promising: IRSID continuous steelmaking and the Energy Optimising Furnace (EOF). The IRSID process does not require time for charging and tapping with operating costs similar to the conventional BOF. The EOF offers much higher scrap melting capability but suffers the same drawback as EAFs: limited products and high sulfur levels. Both processes have lower capital costs but Fruehan (1994) concludes that these processes should be considered for new capacity additions but not for displacement of existing BOF capacity.

SCRAP-BASED METAL PRODUCTION

Electric arc furnaces represent another method of producing steel. Over the period from 1970 to 1990, annual world steel production increased by 175 million tons. Production from scrap-based electric arc furnaces accounted for 75% of this increase (Gooday and Labson 1993, p. 63). Innovation, the relative prices of scrap, iron ore, electricity, and coke, as well as demand for products made from lower quality steel, such as bars and small structural shapes, have contributed to this rise (Barnett and Crandall 1986, pp. 1, 9). Further, EAFs are forecast to compose 60% of new steelmaking capacity by 2010 (Prideaux 1993, p. 3).

The production process using an EAF requires fewer steps than integrated steel production. Operators charge the EAF with either scrap or DRI, eliminating the need for raw

material preparation, such as coking and pelletization of iron ore fines. Using vast amounts of electricity, the EAF melts the charge into liquid steel. The slag is removed, and the liquid steel proceeds to a ladle furnace, where added alloys produce the desired quality of steel (Gooday and Labson 1993, p. 63). Finally, continuous casting of the liquid steel into billets, the smallest semi-finished shape, and blooms and their rolling into final products ensues.

Although integrated producers also use EAFs for producing steel, minimills have been gaining market share. Minimills use EAFs to produce steel products, such as wire, bars, and rods, at relatively lower cost. Higher labor productivity, lower wages, specialized manufacturing of fewer products, lower capital costs, and availability of low-cost scrap have contributed to the success of the minimill sector (Barnett and Crandall 1986, pp. 20-4). With recent advances made in thin slab casting technologies, minimills are now expanding into flat-rolled steel product markets (Unsworth et al. 1989, p. 1-20). However, limited supplies of high quality scrap and, to a lesser extent, the availability of inexpensive electric power will substantially brighten the prospects for the scrap substitutes discussed above.

Parallel to this growth in scrap substitution possibilities are efforts to improve the productivity and flexibility of the electric arc furnace. For instance, continuous off-gas monitoring systems developed by BOC Gases allows more effective optimization of the mix of scrap, DRI, and other scrap substitutes (Isenberg-OLoughlin, 1997, p. 34) and more accurate environmental compliance measures. In contrast, Praxair Inc. advocates the so-called "foamy slag" approach, recommending intermittent rather than continuous monitoring. Post-combustion using the foamy-slag method results in power savings of 4.5 kwh/Nm³ of oxygen (Isenberg-OLoughlin, 1997, p. 36). There are also processes that can melt scrap with less energy using scrap preheating, such as shaft furnaces developed by Fuchs. This company is also developing a furnace that can tap without tilting.

Harbison argues that greater scrap substitution possibilities may spur the development of a steelmaking vessel with the flexibility to span both EAF and BOF operating conditions, such as tap-to-tap time, decarbonization rate, and charge carbon potential (Isenberg-OLoughlin, 1997, p. 38). This hybrid EAF could have a deeper steel bath to allow greater oxygen injection rates and significantly increased decarbonization rates. In fact, Mannesmann Demag's Conarc technology is installing a Converter Arc Furnace (CAF) at India's Ispat Industries, Ltd. that has a twin-shell configuration to combine the advantages of the oxygen converter and the EAF. The Conarc melter has a tapping weight of 180 metric tons, capable of operating with scrap, hot metal, pig iron, and hot and cold DRI. In addition to increased flexibility in charge, future EAFs will have multifuel capability.

Dust from electric arc furnaces are classified as a hazardous waste in North America, Europe, and Japan. The Waelz kiln process has been the traditional method to recover zinc from EAF dust for treatment costs ranging from \$3 to \$5 per ton of steel in the US. The MRT and Ezinex processes recover high quality zinc at reasonable operating costs (Wrona, 1997, p. 61). Once stabilized, the dust is disposed in a landfill. The Center for Material Production and the Steel Manufacturer's Association are studying methods to reduce the volume of dust generated during steelmaking. Continuous scrap charging and preheating technologies, such as the Consteel process, reduce dust discharged from the furnace by eliminating a back charge and, in

most cases, the initial charge. New electric arc furnace dust treatment processes such as All-Met, Horsehead Resource Development's Total Recycle process and Phillip Environmental's IBRD-ZIP process recover both zinc and iron and produce minimal by-products, provide EAF producers a virtually zero waste technology.

CASTING

The pace of technical innovation in this segment of the steel production process has also been brisk. After the widespread adoption of continuous casting by integrated steel producers in the 1980s, thin slab casting, pioneered by Nucor, is taking the industry by storm. More than 20 million tons of thin slab casting will be coming into production by the year 2000 in the US. Strip casting is now a reality in aluminum and stainless steel and is on the horizon for carbon steel.

Direct strip casting offers higher productivity at lower capital cost. For example, Kaiser Aluminum & Chemical Corp. is developing a "micromill," for producing aluminum can stock with a production capability of 35,000 tons per year with a capital cost of less than \$1,000 per ton. Davy International, Fata Hunter Engineering, and Pechiney Aluminum Engineering also have introduced thin strip caster designs. Aluminum can producers in France, Turkey, Luxemborg and in the US (Huntingdon, TN) are installing these new generation machines. These machines produce strip faster and thinner, thus increasing productivity.

There also appears to be a significant effort to commercialize these technologies in the steel industry. Offering advantages similar to those realized by aluminum producers, steel strip casting could potentially increase yield and product flexibility while reducing operating costs and mold slag related defects. Key players in the stainless strip casting area include Nippon Steel/Mitsubishi, Thyssen/Usinor Sacilor, Pacific Metals/Inland, Rosco, Krupp/Thyssen/Voest Alpine, Mannesmann Demag/SSAB/Rautaruukki/Krupp Hoesch Stahl/Preussag, Sumitomo, Bristish Steel, and a consortium of Canadian steelmakers. The disadvantages stemming from the small scale of these technologies, however, may outweigh their capital and operating cost advantages.

CHAPTER III. EMISSIONS FROM THE IRON AND STEEL INDUSTRY

It has long been recognized that production and consumption activities result in discharges of residuals to air, water, and land (Kneese et al. 1970). Materials are not consumed, disappearing into a void, but are transformed into useful products and residuals discharged into the environment. The generation of these residuals generally increases as living standards rise. However, the capacity of the environment to assimilate the ever-increasing amounts of residuals is limited. With increasing appreciation and willingness to pay for a clean environment, more attention has been directed to the abatement of residuals generated during production and consumption.

Coke, iron, and steel are important industries in many countries of the world including the US. They are large consumers of materials, and energy, and generate substantial amounts of air, water, and solid waste residuals. The purpose of this chapter is to identify and elaborate on the factors that influence the mix and quantity of pollutant discharges to air, water, and solid waste media in the iron and steel industry.

COKEMAKING

Conventional by-product recovery cokemaking is a relatively dirty process, discharging pollutants to air, water, and land. Prominent among air emissions are ammonia, benzene soluble organics (BSOs), particulates, SO_x , and VOCs. These emissions occur during charging, coking, quenching, and as leaks from offtake lids and coke oven doors.

Waste ammonia liquor is one of the larger water effluent streams from cokemaking. Other discharges include oil and grease, ammonia-nitrogen, cyanides, thiocyanates, phenols, benzene, VOC, polynuclear aromatics. Trace metals including antimony, arsenic and selenium are also found in effluents from cokemaking.

EPA lists seven hazardous solid waste streams associated with cokemaking. They include:

- process residues from coal tar recovery (including sludge),
- tar storage tank residues, residues from light oil processing units,
- wastewater sump residues, residues from wastewater sumps and
- residues from naphthalene recovery.

These residues are listed under the Resource Conservation and Recovery Act (RCRA).

Many of the air and solid waste organic waste streams are absent in non-recovery coking on account of the complete combustion of volatile organics emitted during the coking cycle¹.

¹ While there is a loss of revenue from not producing organo-derivative chemicals in non-recovery coking, the revenue can be made up by resorting to heat and power recovery from the exhaust.

IRONMAKING

The two major sources for pollution during ironmaking are the sintering process and the reduction process carried out in the blast furnace. Emissions during sintering occur during raw material handling, during discharge, and from the wind box. Emissions from the wind box include particulates, iron oxides, SO_x , carbonaceous compounds, fluorides, ammonia, and metal. At the discharge end, the releases consist of iron and calcium oxides. The sintering processes discharges oil and grease, ammonia-nitrogen, cyanide, phenolic compounds, and heavy metals.

The blast furnace is the largest emitter of CO_2 from iron plants. Significant amounts of CO , SO_x , PM, and NO_x are also released. Emissions from the blast furnace are primarily particulate matter released during tapping, and casting, as well as during drilling and plugging tapholes. The waste generally consists of iron oxides and magnesium oxides. Trace amounts of heavy metals - cadmium, chromium, lead, manganese, and nickel - are found in the particulates. The blast furnace is a large user of water, using approximately 6000 gallons of water per ton of iron produced. Ammonia and cyanide are the notable pollutants in wastewater from the blast furnace. Water emissions comprise of dissolved solids, ammonia, sulfides, phenols, and trace heavy metals, oil and BOD. The sludge from the wastewater treatment plant attached to the ironmaking unit often contains significant amounts of zinc and lead. Slag formation amounts to 15 to 35% of the molten iron production. AISI reports that each ton of hot metal generates approximately a quarter ton of slag. It consists of silicon, aluminum, calcium and magnesium. Slag finds various uses in the market. The blast furnace does not produce any significant quantity of hazardous solid waste.

CO_2 emissions constitute the single largest pollutant to air from coking, ironmaking, and steelmaking operation. Data from Voest Alpine provides a basis for a comparison of the ' CO_2 efficiency' of alternative technologies. Conventional iron and steelmaking produces the largest emissions of CO_2 . Hybrid mills that use DRI and EAF emit significantly less CO_2 . Minimills emit the least CO_2 . Figure 2 presents these emissions coefficients.

In comparing greenhouse gas emissions of alternative technologies, it is important to trace the primary source of energy. Electric Arc Furnaces rely exclusively on electrical power. In a life-cycle analysis, this fact does not absolve the technology of producing green house gases because the purchased electricity may be generated at a coal-based utility. In evaluating the environmental performance of EAF, it is necessary to associate electricity use with a CO_2 emission factor, and only then compare with traditional steel technologies.

STEELMAKING

CO , $\text{PM}_{2.5}$, and NO_x are emitted in large quantities during steelmaking. SO_x emissions depend upon the amount of sulfur trapped in the iron from the blast furnace. Electro-refining of iron in an Electric Arc Furnace generates the largest amount of pollutants, chiefly particulates. These particulates contain all the contaminant metals in the iron. Thus, chromium, manganese, copper and nickel are found on EAF particulates as well as in EAF slag. For this reason, slag from the EAF is generally not a saleable commodity. EAFs that process galvanized iron scrap tend to

produce zinc-rich dust that also includes lead and cadmium. During steelmaking various kinds of scrap and oily mill scale are generated. Home scrap, generated during various finishing and shaping operations, is recycled back to the EAF/BOF. The pickling process during steelmaking, in which the contaminated coating on steel is removed with HCl, generates water emissions with suspended and dissolved solids.

Figure 2: Comparison of CO₂ emissions across alternative technologies

Source: VAI (Sapphire: Advanced Solutions for Waste Free Iron & Steel Plants)

FACTORS AFFECTING EMISSIONS

The conversion of iron ore to steel is a complex process involving various processes, raw materials, equipment, and physical/chemical reactions. Emissions during these processes are a function of several factors, the more important of which are discussed briefly.

Raw Material Quality

Quality parameters that influence environmental releases include the sulfur content of coal, iron content of ore, BTU (or fixed carbon) content of fuel, and impurities in raw materials. These are discussed below:

Sulfur Content

The sulfur content of coal has a direct bearing on emissions of SO_x and H₂S during the coking process. Russell and Vaughan (1976) report that as an approximation, the percent sulfur in coke oven gas is 1.7 times the percent sulfur in coal input to coking units. Sulfur in coal also affects the sulfur content in pig iron, which necessitates a hot metal desulfurizing step during steelmaking.

Iron Content of Ore, and Ore Type

The iron content of ore determines the bulk that needs to be crushed, transported and handled. These operations are associated with energy use as well as CO₂ and PM emissions. Hence processes that use less ore, *ceteris paribus*, are associated with less emissions and higher energy efficiency.

Fuel Choice and Quality

The quality of industrial fuels - coal, fuel oil, residual oil, and natural gas - determine the amounts of criteria pollutants, and metallic hazardous air pollutant emissions from industrial combustion sources within an iron and steelmaking plant. For example, the BTU content of a coal determines the total mass of fuel that must be transported, crushed and conveyed. Hence, a low BTU coal, even if priced at a discount in the market, exacts its full cost, albeit on the environment.

All contaminants in the fuel - whether sulfur, nitrogen, ash, or heavy metals - are discharged to air, water, or land upon combustion, unless controlled with pollution abatement technologies. For example, the ash in coal typically reports to slag. The higher the ash content, the greater is the slag generated during the reduction process. Coal and residual oil contain significantly more sulfur than does natural gas. Processes that use natural gas as the reductant generally have an advantage over those using coal². Coal based (and petroleum coke using) processes also produce a DRI with higher sulfur, which might necessitate a desulfurizing step imposing additional costs during steelmaking. The ash content and the heavy metal content of coal are largely captured within the slag formed during reduction.

Physical form

The physical form of raw material inputs has a profound impact on energy and environmental discharges during coking and ironmaking. The degree to which a raw material must be prepared determines the amount of energy used, and discharges to the environment. The use of fine ore necessitates agglomeration prior to reduction. The sintering/agglomeration plant is a source of significant particulate matter and emissions of other pollutants. A substantial amount of energy may be consumed in the iron-ore agglomeration or pelletizing plant, as well as the coal preparation plant. In some cases, part of the energy is derived from recycling heat or fuel from other processes. In other instances, the use of fossil fuels generates CO₂ and other emissions. Renaud (1995) points out that power consumption for grinding coal to a coarser size is less than half the power consumption for pulverizing coal to a fine size. Emissions associated with the consumed power would also be similarly characterized.

The physical form of raw materials partly determines the efficiency of the reduction process. While finer raw materials promote mixing and faster reaction, they also create material handling and burden support problems. Too fine an ore may cause entrainment in the blast furnaces, where it may be carried away with air exhausted from the unit. Besides process problems, the physical form of raw materials may influence certain emissions during raw material preparation and feed charging. Iron ore occurs in the form of fines, pellets, and lumps.

² www.newsteel.com/features/1096f4.htm

Coal too is available in many sizes ranging from -6mm to -32 mm. Transport and handling of iron ore fines and pulverized coal releases some fine iron ore and coal particles in to the immediate atmosphere. Processes that use lumpy ores and coarser coals, or processes that bypass the use of raw materials will naturally be associated with less particulate emissions.

Impurities in Inputs

Chatterjee (1993) reports that the amount of slag generated during ironmaking is directly related to the amount of gangue present in the iron feed in the heat. The ash content of coal is a factor in the generation of slag in blast furnace operations. Since the removal of ash (silica) generates CO₂ during slag formation, higher silica content in coal and iron ore generates incremental CO₂ emissions. Chatterjee (1993) further asserts that good quality coals with low levels of ash, sulfur and volatile matter are likely to yield higher fuel efficiency, and require less additives (fluxes and desulfurizers). Similarly, EPA (1999) reports lead emissions in particulates from EAF operations are a function of the lead in the scrap charged to the process.

In other cases, the strength and quality of reagents as well as operating practices may determine emissions. A case in point is the emissions of polyaromatic hydrocarbons (PAH) emissions during the quenching operation in cokemaking. Quenching performed with contaminated waters releases order of magnitude higher amounts of PAH than quenching with clean water.

Control Equipment

Both the choice and efficiency of pollution control equipment has an important impact on emissions in iron and steel production. There is substantial diversity in the type and efficiency of pollution control equipment in the industry that complicates estimation of emissions at the aggregate level.

Choice of Control Technology

Numerous pollution abatement technologies are available. These technologies are typically specific to one medium - air, water, or solid. Within each medium however, several variants exist that control one or multiple pollutants to different degrees. Particulate abatement equipment include simple cyclones, high efficiency cyclones, electro-static precipitators (ESP) with a continuum of efficiencies, scrubbers, wet ESPs, fabric filters, and ceramic filters. Cyclones achieve about a 90% control of particulates by mass. However, their capacity to control finer particles ($< 10 \mu m$) is generally limited and diminishes rapidly with decreasing particle size. Removal efficiencies decline rapidly as particle size is reduced. Cyclones are often used as the first stage or preliminary particulate removal device. ESPs and wet scrubbers can be tailored to meet requirements. Their efficiencies depend on the size of the plate area and voltage applied in the case of ESP, and on the pressure differential in the case of scrubbers. Fabric filters are required when gases must be cleaned of micron size particles. Ceramic filters are relatively new entrants. They achieve very high degree of fine particulate cleaning.

Whether the steel industry achieves simultaneous reductions in multiple pollutants is in part determined by how the regulations are written. The pollution control equipment industry provides the means to control multiple pollutants. The SO_x - NO_x - ROX Box developed by

Babcock Wilcox simultaneously controls several criteria pollutants. The wet scrubber or the venturi scrubber is an excellent example. It effectively controls particulates, SO_x , and even some water-soluble acid gases and organics. Installing scrubbers increases the overall efficiency of pollution control from a societal perspective. However, if the regulations are framed focusing on one pollutant at a time, opportunities for such synergistic reductions in multiple pollutants may be lost.

Efficiency of Control Technology

The control efficiency of pollution control equipment is an important determinant of emissions from coking, ironmaking, and steelmaking technologies. Equipment specifications as well as operator practice determine the actual control efficiency of pollution control equipment. Pollution control equipment is available in a range of efficiencies. ESPs are available in various sizes where size is measured in the amount of plate area per 1000 actual cubic flow per meter (acfm). The larger the specific area, the higher is the achieved efficiency of control. Even when two firms operate an ESP with identical input concentrations and identical equipment size, actual performance may vary on account of operational practices. One firm may apply a higher voltage differential across the ESP plates than the other, and therefore achieve higher control of particulates. Fabric filters may be purchased with different bag surface area to flow rate ratios. Similarly, the efficiency with which venturi scrubbers control particulates depends on the pressure differential, which in turn is controlled by the diameter of the venturi throat. These aspects are important determinants of emissions from process units. They also highlight the danger of measuring or perceiving pollutant control exclusively in terms of the purchased control technology. One implication, for example, is that it is theoretically incorrect to use an emission factor from one ESP to compute emissions inventory at another plant with an ESP if the two ESPs do not match in specifications and operating practices.

Process Characteristics

Process characteristics are an important influence in determining emissions. The efficiency of input use, the type of fuel required, the energy-efficiency of the process, provisions for the use/recycle of by-products are important determinants of overall emissions from the process.

Many coke, iron, and steelmaking technologies and processes produce significant amounts of by-products. The ability to gainfully recover/recycle by-products is critical to the success of several iron and steelmaking technologies. Integrated iron and steel mills recover and recycle fuel value and heat from coking, and blast furnace off-gases in other processes within the mill. By-product coke plants recover various organic chemicals from coking off-gases. Non-recovery coke plants, on the other hand, facilitate generation of power from off-gases. The choice of technology is also dictated by the prices and opportunity costs of marketable and non-marketable by-products of the process. To the extent that by-product generation is associated with discharges to the environment, technologies that recover and re-use by-products are environmentally superior to those that do not.

One of the advantages of the COREX technology is its inherent de-sulfurizing capability³. The COREX process adds limestone, coal, and iron ore to the reduction furnace. During reduction of iron, the sulfur in coal is transferred to calcium from the limestone to form gypsum, which is removed in the form of marketable slag. The environmental friendliness of COREX contrasts with by-product recovery coke ovens where the sulfur in coal may be released as H₂S and SO_x.

Scrap-Using vs Raw Material Using Technologies

An obvious source of difference in emissions across different iron and steelmaking technologies is the use of scrap in hot metal production. Since steel scrap has already undergone the purification process, its re-melting does not generate as much emissions. Thus, all pollutant discharges associated with handling ore, preparing coal, manufacturing coke, producing sinter, and producing iron are influenced by the substitution of scrap for conventional ironmaking raw materials.

Coke vs Coal Using Technologies

Secondary to scrap consumption, the degree of substitution of coal for coke in the ironmaking step is an important determinant of emissions. Pulverized coal is gaining acceptance in the steel industry as an affordable substitute for coke. Traditional byproduct cokemaking processes are associated with the discharge of pollutants during pushing and quenching stages. These pollutant emissions are partly avoided by switching to pulverized coal. Technologies such as COREX provide steel-makers with flexibility in fuel choice as well as the advantage of an environmentally friendlier production process.

Batch vs Continuous Processes

Some of the older cokemaking processes, as well as steelmaking operations are batch processes. Batch processing involves discontinuous processes that generate emissions during transfer, as well as require more energy for transport and re-heating. For example, the raw material, such as hot coke, may emit pollutants even as it is being transferred. Hence, batch operations tend to be less productive and less energy efficient than continuous processes. Within batch operations, plants with large batch operations may pollute proportionately less than plants with smaller batch operations. That is, smaller and more frequent batches require more frequent intervention in the form of door removal, pushing, quenching, and other operations. Such processes are therefore associated with more emissions.

Continuous systems carry out the entire reaction in a single stage and, hence, are associated with much lower emissions. The Calderon coking process discussed earlier is an example of a continuous system, which reduces process emissions. Continuous casting of steel into slabs is another example of continuous processes. Continuous casting eliminates labor, energy, capital, storage and time requirements associated with batch production of steel slabs. Russell and Vaughan report that combustion residuals associated with reheating ingots (and electricity generation) as well as waterborne milling residuals (BOD, oil, and suspended solids) would decrease if continuous casting were adopted. The amount of scrap generated would

³ http://www.fe.doe.gov/coal_power/fs_corex.html

decrease too. Recently⁴, NKK, Japan announced the supply of world's first continuous rolling mill. The mill is intended to operate downstream of a continuous casting machine. NKK reports higher productivity, as well as reduced losses (reduced scrap generation) as well as savings in labor costs. Energy losses associated with re-heating products too would be saved with a continuous rolling mill that receives its feed from a continuous caster.

Open vs Closed Systems

Generally, batch operations are open systems, with distinct steps involving transfer of materials. These operations give up heat to the surroundings and are inherently less energy efficient because of the energy loss and time expended between batches and between different operations. In closed systems, there is limited, if any, potential for gases to escape the systems, except after combustion, and treatment.

Positive (High, Low) Vs Negative Pressure Operation

The traditional coke ovens generate much pollution precisely because the operations are conducted under pressure⁵. Consequently leaks from doors and lids are common, especially at the beginning of the coking cycle when pressure from the release of volatiles is high. In contrast, the Jewell non-recovery coke ovens operate under negative pressure. Operation under negative pressure ensures that pollutants are not emitted to the surroundings even if leaks were present.

Byproduct vs Non-Recovery Coking

Another fact that determines emissions during coking is whether the technology seeks to maximize value to the firm by recovering the organics emitted during the coking process. Traditional coke ovens collect these emanations, and incidentally, release some organics. Non-recovery coke ovens, such as the Jewell coking technology, combust all organic gaseous compounds during coking. Hence non-recovery coking processes emit significantly less environmental emissions and constitute a much smaller hazard than traditional recovery coke ovens.

Degree of Combustion

The amount of excess air, temperature of combustion, residence time, and mixing determine the degree of combustion of organic gases. Higher temperature combustion with intimate mixing of gases with combustion air, and sufficient residence time ensure near total destruction of organic species. Processes that completely combust organic gases (such as non-recovery coking) emit less number and amount of organic pollutants⁶.

EPA's background document for AP-42 emission factors for coke production points out that the composition of coke oven gas emitted during coking varies as the coking cycle proceeds. It is likely that the volatiles are emitted in early phases of coking and the less volatile heavy hydrocarbons toward the end.

⁴ NKK Japan (www.nkk.co.jp) (Mr. Ryosuke Nishiyama 03-3217-2138)

⁵ In fact, positive pressure is an operational necessity. Any ingress of cooler air in to the oven could damage the ovens.

⁶ though, complete combustion at high temperature may marginally increase NOX emissions.

Duration of Operations

Some processes take longer than others do to achieve the desired degree of completion. The duration of a coking cycle is inversely related to the temperature of the oven walls (U.S. EPA, 1987). If door leaks and 'slips' are random events, then the longer the duration of a process, the more likely is it that emissions are greater from the process. The duration of the coking cycle indirectly affects emissions from the process by determining the number of pushing operations required during the process.

High temperature Vs Low temperature process

The duration of a coking cycle varies inversely with oven wall temperature (See Figure 3). Temperatures of coking operations may be a determinant of emissions for two reasons. First, if door leaks and slips are proportional to the duration of combustion, clearly then longer duration cycles will be associated with more leaks. Second, higher temperature combustion is likely to generate incrementally more NO_x emissions during coking.

Figure 3: Coking duration vs wall temperature

Source: EPA (1987)

The degree of iron ore reduction is a function of the temperature of the reducing gas. In turn, the temperature of the reducing gas is a function of the volatility content of the coal. More volatile coals yield a lower temperature reducing gas (Chatterjee, 1993). Higher degrees of reduction require higher quality coals. Temperature, specifically, combustion temperature influences thermal NO_x formation. The higher the peak temperature, and the longer the duration for which gases experience this temperature, the higher are NO_x emissions from the process (epa,

1994). Blast furnace operations are carried out at higher temperatures than DRI processes, and thus are associated with higher NO_x emissions.

Desired Degree of Metallization

The desired degree of metallization of reduced iron affects its residence time in the reduction chamber, and energy use in this step. For any given technology, energy use increases as the desired degree of metallization increases, (and increases sharply when the theoretical maximum degree of metallization is neared). Consider a blast furnace producing a product with iron content of 90%. To achieve a product with 93% iron content, the iron-maker might have to increase the processing time in the furnace, &/or increase the mixing of the constituents, &/or use higher quality coke, or add another stage to further reduce carbon in the burden. Significantly higher inputs of raw materials, and reactant concentrations may be required to affect a 3% increase degree of iron content in pig iron. Energy requirements and reductant requirement increase even further as an iron-maker pushes the process toward its theoretical maximum iron content in product. However, higher carbon content in the iron-forming step might offset resource use and cost during steelmaking. This is especially true of DRI.

Product quality

The quality of coke is measured by the residual volatile content, its sulfur content, as well CSR number, and ash content. If higher coke quality is desired, it is necessary to input low-volatile metallurgical or other high-quality coal, and 'cook' the coal for a longer duration. This increases costs not only because higher quality raw materials are more expensive, but also because the productivity of the coke ovens slips due to longer coking cycles. Benzene Soluble Organics (BSOs) from coke during pushing depends on how much the coke is 'cooked'. Less cooked 'green coke' emits more BSOs. Emission factor of polyaromatic hydrocarbons (PAH) for green coke (1.17 g/mt) is three times the emission factor for non-green coke (0.419 g/mt) (epa, 1979). Figure 4 depicts this relationship for emissions of 7 PAH aggregate.

Regulatory Standards and Monitoring Stringency

Environmental discharge standards play a n important role in determining emissions from iron and steelmaking processes. Environmental standards influencing the choice of pollution control equipment is well established. Lax standards on particulates and SO_x may be complied with using cyclones and low sulfur coal. Conversely, stringent standards necessitate higher efficiency equipment such as ESP, scrubbers and flue gas desulfurizing units. Given an incentive exists to choose the least expensive (which happens to be more polluting) technology, the stringency of environmental standards play a primary role in determining emissions from (new) plants. In other words, environmental standards that a new firm must comply with, is a factor in its choice of process technology, and in turn influences the magnitude of pollutant discharges from the plant.

Whether the industry achieves simultaneous reductions in multiple pollutants is in part determined by how the regulations are written. If the regulations are written to simultaneously achieve control of multiple air and water pollutants, then firms have the incentive to seek out process changes as well as add-on controls that abate multiple pollutants. On the other hand, focus on one pollutant at a time, typically results in sub-optimal control from a society's

perspective. Control of emissions from the basic oxygen furnace is an example. Many steelmakers have installed venturi scrubbers. Others have installed ESPs. The wet scrubber effectively controls particulates, SO_x , and even some water soluble acid gases. Installing scrubbers increases the overall efficiency of pollution control from a societal perspective. However, if the regulations exclusively limit particulates, then firms have no incentive to choose a scrubber over an ESP, thus squandering valuable opportunities to control jointly released pollutants.

Figure 4: Relationship between % green coke and PAH emissions

Source: EPA

The U.S. Environmental Protection Agency has several layers of regulations affecting coking, ironmaking, and steelmaking units. These include Best Practical Control Technology (BPT), Best Conventional Control Technology (BCT), Best Available Technology Economically Achievable (BAT), New Source Performance Standards (NSPS), Pretreatment Standards for Existing Sources (PSES), Pretreatment Standards for New Sources (PSNS). These standards require control of different pollutant groups to different extents. Units subject to NSPS are generally the cleanest while the BPT and BCT are relatively less stringent technologies.

The stringency of monitoring, enforcement and compliance is yet another factor that affects emissions. EPA bases much of its inventory calculations assuming full compliance. Assumption of full compliance is often justified because certification is often based on the installation of complying pollution control equipment. However, when equipment efficiency may be changed to decrease operating costs, there arises the potential for non-compliance. Such is the case with the operation of the ESP, and the wet scrubber where efficiency of control changes with voltage applied or with the pressure differential across the venturi throat. Since operating costs increase with higher voltages, and with higher pressure differentials, some firms may operate in non-compliance. Non-compliance is likely when the chances of detection, prosecution,

and adverse judgment are low, and when the potential penalty is less than the opportunity cost of non-compliance.

Economic Variables

Economics factors may not seem influential in determining emissions, but may play an important role. At an industry level, aggregate emissions are justifiably related to aggregate production. This being the case, imports of iron and steel products displace domestic production, and, therefore, reduce aggregate domestic emissions⁷. Trade policy interventions have repercussions on regional environmental discharges. The projected imports of coke is a case in point. Stringent regulations on cokemaking in the US are likely to result in plant closures, substitution away from coke, and to the import of coke. If, as seems likely, emissions standards for cokemaking are less stringent elsewhere, then environmental standards in the US may result in higher carcinogenic emissions in foreign countries.

Prices for variable inputs, in particular for fossil fuels of different types and qualities determine the relative use of coke, natural gas, coal, and liquid petroleum products as fuels. These fuels, upon combustion, produce differing amounts of CO₂, and SO_x. Any change in the price of coke, caused by economic, regulatory, technical, or trade policies or developments, would have a short-run, and a long-run impact on coke use in blast furnaces, and therefore a corresponding change in emissions.

In this context, the availability of fuels and the location of iron and steel facilities are important. A firm sited close to a high-sulfur coal mine is very likely a user of the high sulfur coal on account of avoided transportation and other costs. Another firm with access to inter-state natural gas pipeline, may choose to use a gas-based technology because natural gas is the least-cost carbon based fuel available to it. Excepting the possibility that coal-based technology is more efficient than gas-based technology, the coal-consuming firm will report higher emissions of SO_x than the firm using gas based technology. In this manner, the relative prices for variable inputs play an important role in determining emissions.

⁷ Emissions are not reduced per se. They are exported to the exporting nation. Depending on technology used domestically and abroad, net global emissions may stay the same, increase, or decrease following trade. Often, competitive advantage is gained from better technology and lower cost factor inputs. Sometimes, the avoided cost of environmental regulations may also influence product price. Competitive advantage gained on the basis of avoided environmental cost could result in higher net global environmental emissions.

CHAPTER IV. THE ENVIRONMENT & NEW STEEL TECHNOLOGIES

Firms invest in new technology considering investment and operating cost relative to productivity, product quality, and environmental performance. Capital retirements as well as rapidly changing technology are motivating many firms to compare existing and emerging technologies on the basis of economics and environmental performance. While a full comparison must necessarily consider capital costs and a host of other factors, data limitations limit comparison to resource requirements and emission factors for important air, water, and solid waste discharges.

We compare alternative cokemaking, ironmaking, and steelmaking technologies. Within ironmaking, a distinction is made between smelting processes that produce liquid iron, and DRI processes that produce reduced iron in solid form. All observations and inferences are conditional on the accuracy of reported resource use and emissions coefficients.

COKING TECHNOLOGIES

The baseline coking technology is represented by the by-product coking technology. The non-recovery coking technology marketed by Sun Coal Company represents the MACT technology as defined by the Environmental Protection Agency. Absence of resource use data and limited data on Thyssen cokemaking precludes its consideration. Finally, Calderon Coking represents an emerging (but not commercially proven) technology.

Table 1 presents the resource use as well as emissions coefficients for important pollutants in various cycles of coking operation from alternative coking technologies. The three coking technology require coal in different amounts. It takes 1.54 tons of coal to produce a ton of coke with the non-recovery cokemaking technology. At the other end, Calderon Coking claims to produce a ton of coke from 1.43 tons of coal. Since the volatile constituents vary from coal to coal, the resource use coefficients may or may not be indicative of input use efficiency.

In general, non-recovery coking is associated with lower emissions than by-product coking with the most noticeable difference, expectedly, in VOC emissions. Non-recovery coking, on account of operation under negative pressure and full combustion of all gases, releases little if any of the toxic hydrocarbons that by-product coking does. Calderon coking - a high pressure but fully enclosed and continuous process - also promises minimal environmental releases during coking.

SMELTING TECHNOLOGIES

While several iron smelting technologies exist, COREX is a commercially available technology that competes with traditional blast furnace technology. DIOS is a Japanese technology that has been under pilot plant study for several years.

Table 1: Resource use and environmental performance of coking technologies

COKING TECHNOLOGIES				
	Units	Technology		
		By-Product	Non-Recovery	Calderon
Resource Requirements				
Coal	tons/ton coke	1.47	1.54	1.43
Electricity	Kwh per ton coke	125		
Steam	MMBTU/ton coke	1.14		
Water				
Air Emissions				
PM/Dust				
Charging	Lbs/ton coal	0.00055 - 0.77	0.009 - 0.029	0.02 ^c
Coking/Combustion	Lbs/ton coal	1.08 - 3.75	0.98 - 1.46	
Pushing	Lbs/ton coal	0.018 - 1.28	0.47	
Quenching	Lbs/ton coal	0.33 - 5.78	0.64 - 1.96	
SO _x				
Charging	Lbs/ton coal	0.02	0.00675	0.32
Coking/Combustion	Lbs/ton coal	11.7	10.53 - 10.66	
Pushing	Lbs/ton coal	0.0374 - 0.1408	0.00843	
Quenching	Lbs/ton coal		0.0053	
NO _x				
Charging	Lbs/ton coal	0.03	0.03	
Coking/Combustion	Lbs/ton coal	1.35	0.727 - 1.00	
Pushing	Lbs/ton coal	0.02 - 0.022	0.045	
Quenching	Lbs/ton coal	0.33 - 5.78	0.002	
PAH				
Charging	Lbs/ton coal			0.156-1.9(a); 15.5-46.4(b)
Coking/Combustion	Lbs/ton coal	0.018 - 0.033		
Pushing	Lbs/ton coal			
Quenching	Lbs/ton coal			
	g/ton coke	29		
VOC				
Charging	Lbs/ton coal	2.5 - 2.76	0.000032	
Coking/Combustion	Lbs/ton coal	0.525		
Pushing	Lbs/ton coal	0.1	0.000076	
Quenching	Lbs/ton coke		0.001	
	g/ton coke	730 - 2800		
a: Clean Quench Water b: Dirty Quench Water c: 0.038dust; 0.01PM2.5 d: Lower range represents quenching with clean water, upper range quenching with dirty water				

Comparison of resource use across technologies is complicated by the substitution possibilities between inputs. In other words, while resource use coefficients presume a 'Leontief'-type technology, iron makers often substitute between different kinds of iron ore, coke, coal, scrap, DRI, and other factors of production. These substitutions also affect observed emission factors.

Table 2: Resource use and environmental performance of iron technologies

IRON ORE REDUCTION				
	Units	Technology		
		Blast Furnace	COREX	
Resource Requirements				
Iron Ore	Kgs/thm	1600	1487 (1344 - 1609)	1450
Coal		up to 33% with PCI	1175 (1050 - 1345)	952
Coke	Tons/ton	0.3 - 0.45	0	
Electricity	Kwh per ton	22 - 34	60	
Oxygen	Nm3/thm	07	656.8 (525 - 788)	608
Labor	Manhrs per thm	0.3	0.6	
Air Emissions				
CO2	Tons/thm		0.4 - 0.6(a)	
PM/Dust	g/thm	590(b)	130	
SOX	g/thm	760 - 1410	53	
NOX	g/thm	12.25 - 100.7	114	
Methane	m3/thm		16.5 - 17.28	
Water Emissions				
Ammonia	g/thm	900(c)	60	
BOD	mg/Kg	6.2097		
Sulfides	g/thm	180(c)	0.01	
Phenol	g/thm	3.8(d)	0.04	
Solid Waste Emissions				
Slag	Ton/thm	0.25	0.42	
Dust and Sludge	Kg/ton	17.5 - 25	50	
a: 0.6 estimate based on conversion of volume share CO2 to mass using exhaust flow of 1650-1728m3/thm 0.29 t/thm is the stoichiometric estimate; Total CO2 estimate (metallurgical + available process energy) = 1.45 Kgs/ton b: typical of large, new furnaces with local hoods and covered evacuated runners. c: as of 1990 d: 100 g/thm as of 1990 (letter from VAI)				

From Table 2 it is evident that COREX has several desirable features. First, its iron ore input coefficient (1344 - 1609 Kgs per ton) is modestly lower than the 1600 Kgs of iron ore required for blast furnace reduction. It requires modestly higher electricity and more oxygen than does the blast furnace reduction process. Second, the process does not require coke, and hence eliminates,

at least partially, the emissions associated with cokemaking. It is also environmentally superior to blast furnace technology. This advantage derives from the partial use of hydrogen as a reductant rather than complete reliance on carbon. PM and SO_x emissions are significantly lower, though NO_x emissions may be higher than that from the blast furnace. In addition, the use of coal release some methane during the reduction. COREX also boasts of significant reductions in ammonia, phenol and sulfide discharges to water effluents during the reduction process. The technology, however, produces higher amounts of slag, possibly due to the direct inputs of impurity-containing coal in to smelting reduction furnace.

DRI TECHNOLOGIES

There are at least half a dozen, and probably a dozen competing DRI technologies. The evaluation here is limited to those that have are commercially established. All DRI processes in Table 3 consume approximately the same amount of iron ore. FASTMET and Circofer use coal as the reductant, whereas other technologies use natural gas for providing thermal energy and

Table 3: Comparison of Alternative DRI Technologies

DIRECTLY REDUCED IRON TECHNOLOGIES							
	Units	CIRCOFER	CIRCORED	FASTMET	HYL III	HYL 4M	MIDREX
Resource Requirements							
Iron Ore	Kgs/thm	1442	1483	1380 - 1430	1450		1450
Coal		380	0	270 - 380	0	0	0
Coke	Tons/ton	0	0	0	0	0	0
Electricity	KwH per ton	90	100	60 - 90	90		100
Oxygen	(N)m3/thm	190 - 195	0	0	0		0
Natural Gas	Gcal/thm	0	2.75	0.6 - 0.65	2.55 - 2.86	1.97	2.4 - 2.6
Water	m3/ton	2	1.5	1 - 1.5	1.6 - 1.8		1.2
Labor	Manhrs per thm	0.315	0.315	0.2 - 0.3	0.34		0.16
Air Emissions							
CO ₂	Tons/thm			1.05 - 1.18			
PM/Dust		50mg/Nm3	50mg/Nm3		0.039kg/ton		
SO _x	g/thm	10 - 100	10		0.2		
NO _x			86ng/J		0.05kg/ton		
Methane	m3/thm						
Water Emissions							
Ammonia	g/thm						
BOD	mg/Kg						
Sulfides	g/thm						
Phenol		0.1 mg/litre					
Solid Waste Emissions							
Slag	Ton/thm						
Dust and Sludge	Kg/ton				26.7		

carbon & hydrogen for reduction. The DRI processes consume different combinations of reductants, oxygen and energy and other inputs. Midrex DRI is relatively electricity intensive than other DRI technologies. However, consistent with higher labor costs in the US, labor input at 0.16 manhours per ton iron is the least among the set of DRI technologies. Unfortunately, emissions coefficients are missing for many technologies. This is a critical information gap that must be filled to facilitate comparison of environmental performance.

REFINING TECHNOLOGIES

Basic Oxygen Furnace (BOF) technology once dominated the steel industry in the US. The EAF based minimills have, however, gained a substantial share of the steel refining market. A few steel mills employ the Q-BOP process. Table 4 presents the resource use and emissions coefficients for BOF, QBOP, and EAF technologies.

Table 4: Resource use and environmental performance of steel refining technologies

STEELMAKING TECHNOLOGIES				
	Units	Technology		
		BOF	QBOP	EAF
Resource Requirements				
Iron/Scrap	Kgs/thm	0.932	0.8	0.967
Nitrogen	m3/ton		1.13	
Electricity	KwH per ton	101 - 201	30	430 - 600
Oxygen	Nm3/thm	0.097	0.048	350
Labor	Manhrs per thm	0.32		
Maintenance	Manhrs per thm			
Air Emissions				
CO ₂	Tons/thm			
PM / PM10	Lb per thm	0.0068 - 28.5	0.056(a)	0.58 - 38
Dust	Lb per thm	0.117 - 0.220		0.066 - 1.347
SO _x	Lb per thm	0.0038		0.07
NO _x	g/thm	0.02 - 0.1		0.066 - 0.54
Solid Waste Emissions				
Slag	Ton/thm	100 - 440		110 - 420
Dust and Sludge	Kg/ton	8 - 62		20 - 40
Ranges often indicate differences in control equipment				
(a): with venturi scrubber				

The Q-BOP apparently is a little more efficient at converting iron to steel. It is also very energy efficient, consuming only 30 Kwh⁸ per ton of steel, which is at least an order of magnitude lower than BOF and EAF processes.

Data for comparison of environmental performance is hard to come by. The BOF and the EAF generate approximately the same amount of slag, dust and sludge. Emission coefficient ranges overlap for these competing technologies, negating any basis for ranking them.

The above examination of the resource use and environmental performance of alternative coking, ironmaking and steelmaking technologies reveals many data gaps, especially pertaining to emissions coefficients. The only notable observation is the apparent superiority of COREX over the traditional blast furnace reduction of iron both in terms of resource use and environmental performance.

⁸ according to the EPRI

CHAPTER V. THE LIFE CYCLE ECONOMIC MODEL

The sequential nature of production with multiple joint products has motivated many researchers to develop linear programming or process models of the steel production process. Early studies include Tsao and Day (1970) and Russell and Vaughan (1976) while more recent efforts include those by Sparrow, et. al. (1984) and Considine, et.al. (1992). These models are at the industry level with aggregate input-output relations determined either from representative process units or from aggregate industry data.

In contrast, this study develops a detailed process model for a specific steel plant, the Mon Valley Steel Works, owned and operated by U.S. Steel Corporation (USX). The Mon Valley Works includes the Clairton Coke Works, the largest coke oven batteries in the U.S., the historic Edgar Thompson blast furnace and BOF mill developed by Andrew Carnegie, and the Irvin finishing mill. This complex is somewhat unique because it generates excess coke, which is transferred to other USX mills and sold to other steel producers. Nevertheless, this plant is representative of many integrated steel mills in the U.S. because technical efficiencies of coke ovens, blast furnaces, and other equipment do not vary substantially between firms.

The model development occurred in two phases. The first step entails the development of a simple linear programming model based upon estimates of the costs by process based upon data provided by Don Barnett (1997). This information, however, does not provide a very detailed picture of by-product gas, steam, and electric power balances between the various process units in the plant. The life cycle inventory data collected by Rhodes et. al. (2000) provides information to develop these balances and to estimate and the environmental emissions by process. The life cycle assessment (LCA) includes raw material extraction through steel product manufacturing. Both sources of information provide a fairly detailed view of the steel production process, including iron and coal mining, coking, blast furnace production, steel production, and rolling and finishing operations.

THE ECONOMIC PROCESS MODEL

Barnett (1997) collects detailed process data for many integrated steel plants around the world. His data includes input-output relations, factor prices, and capacities by process. Companies operating these plants voluntarily subscribe to his service under the condition that their detailed process cost data remains confidential. Based upon this information, Barnett provides analysis that allows companies to determine where their plant costs rank in relation to others in the industry.

Barnett calculates the average cost of production by process by summing the product of the input-output coefficient and the respective input prices, which provides an average cost per unit of output. The per unit costs of intermediate inputs, such as coke and pig iron, then essentially become input prices for downstream processes, such as steelmaking.

Barnett provided us with his data for the Mon Valley Steelworks. This allowed the specification of a simple linear programming model with 16 process activities. The first two

include screening of metallurgical coal and the production of coke from conventional by-product slot coke ovens. The coefficients of these activities include coal, labor, energy, and maintenance requirements per unit of coke produced as well as an estimate of the amount of coke oven off-gas generated. The next group of activities involve iron production, including sintering, pulverized coal injection, and blast furnace operation. The third group of activities entails steelmaking; including basic oxygen furnace operation, vacuum de-gasification, and continuous casting. The final group of activities includes rolling and finishing operations that produce hot-rolled band, cold rolled steel sheet, and galvanized steel products. Our base model solution provides an estimate of total variable production costs very close to the costs estimated by Barnett (1997).

LIFE CYCLE MODEL MODIFICATIONS

The life cycle inventory data provides considerable detail that permits significant enhancement of the process model initially developed using the information provided by Barnett. The first improvement involves the inclusion of emission coefficients by process. In general, the processes used by Barnett are more aggregate than those defined by Rhodes et.al. The required aggregations are discussed in the next section. Unlike Barnett (1997), the life cycle inventory data includes emissions generated in upstream activities, such as coal and iron ore mining, which are discussed in the second sub-section below. As the previous discussion indicates, our surveys of the industry did not yield a complete emissions profile of new technologies, which necessitates several assumptions that are discussed below.

Finally, a careful comparison of emissions reported by Rhodes et. al. with those from our model provides a good check for accuracy. The complicating factor in this comparison, however, arises from the hypothetical nature of the plant output in their study. As mentioned above, the Mon Valley steel works is imbalanced, producing substantially more coke than required. As a result, the Rhodes study only included those emissions associated with coke requirements at the plant. Other plants consuming the excess coke would include, at least in theory, the associated emissions. From a plant optimization viewpoint, not accounting for these emissions and in particular the off-gases that coke ovens generate would be a serious distortion. This model calibration issue and related matters are discussed in more detail below.

Process Emission Coefficients

In calculating the emission coefficients, the first step was to match processes in the life cycle inventory data by Rhodes to those in the base process model so that emission coefficients from the Rhodes study could be properly assigned to processes within the process model. Comparison of the two models yielded the following associations and subsequent assignments shown in Table 1.

Where single LCA processes are associated with multiple processes, emission coefficients have only been attached to the first of the associated processes listed in Table 1. The units of emissions were given in a variety of units, and all were converted to a pound per short ton basis to match process levels as defined in the existing process model. All emissions were then added to the existing set of commodities.

Table 5: Process associations between LCA and the process model

Model Process Name	Model Process Description	LCA Model Process Code	LCA Model Process Description
COKE-SLOT	Making Coke	8305	Coke Oven Products (mg/MJ)
SCREEN	Coke		
SINTER	Sintering		
PCI	Pulverized Coal Injection		
BF	Blast Furnace	8312	Blast Furnace Iron and Slag (mg/kg)
BOF	Basic Oxygen Furnace	8318	BOF Steelmaking and Cont Cast (mg/kg)
VDG	Degasification		
CAST-CCS	Continuous Cast Slabs		
HRB	HR-Band	8321	Hot-Dip Galvanizing (mg/kg)
HRB-FINISH	HR-Band-Temper & Finish		
HRB-PICKLE	HR-Band-Pickle	8322	Pickling (mg/kg)
CR-TANDEM	CR-Tandem and Clean	8323	Cold-Chamber Anneal (mg/kg)
CR-BA	CR-Batch Anneal		
CR-CA	CR-Cont Anneal		
CR-FINISH	CR-Temper & Finish		
GAL-HD	Galv Hot dipped	8324	Hot-Dip Galvanizing (mg/kg)

No changes were made to the input profiles (materials, labor, operating costs), except in a very few specific cases noted below. The Barnett data did not include the three power plants at the Mon Valley works. Their steam output significantly alters the energy flows within the plant. The life cycle data collected by Rhodes, however, provide a more accurate representation of the plant's energy flows

The first step in incorporating the power plants was to add them as new processes, and to complete their input / output profile. The power plants are at the coke ovens, the steel works, and the rolling mill. Second, the emission coefficients were calculated. This was straightforward, and coefficients were taken from the LCA Model and converted to pounds per MJ of steam produced. Steam is tracked in MJ throughout the model.

Third, power plant fuel inputs and by-product electricity generation were added to the input/output profiles in the proper units. The steam output from the three power plants is clearly assigned to consumption points within the plant and, therefore, each power plant's steam output is designated accordingly. These three items were added to the set of commodities and the set of intermediate products.

Since steam was not yet entered as an input into any process, this was the next and final step to complete for the power plants. There are only four processes that use steam as an input, and these processes were amended to include a steam input in the appropriate units of MJ steam

per short ton of process level. A detailed electricity balance, which appears in Appendix A, indicates that kilowatts of consumption and production are within 5 percent of each other, which may reflect transmission losses and slight discrepancies between the LCA data and Barnett's technical coefficients.

The main solid waste from steelmaking is the slag from the blast furnace and from the steel furnace. Waste slag has no re-use within the plant, and all of the slag exits the steel mill. Waste slag is commonly sold for use in road building and cement production. In the LCA model, waste slag totals 790,000 MT per year. Most of the slag is sold for productive use, and approximately 5% is landfilled as solid waste. In the LCA report, Table 3-4, page 30, the slag figure reported only includes the landfilled quantity, not the slag sold for productive use.

The LCA slag output coefficients were apparently adjusted so that only the landfilled portion is represented. In the present model, all slag coefficients were readjusted upward using the implied waste ratio. Slag exiting the plant as waste is accounted for as a solid waste and landfill costs accrue to the total cost (there are no other costs associated with landfilled slag), while slag sold earns a credit that accrues to the total cost.

Upstream Activities

The next modification includes the addition of six upstream processes: coal mining, iron mining, iron pellet production, flux mining, zinc mining, and electricity generation. The addition of these five processes was straightforward. Emissions were converted to pounds per short ton output and added to the input/output profile for each process. New emissions were added to the commodities and emissions sets as required. Labor, energy, and material inputs were not included because the process model optimizes plant activities not the entire vertically integrated supply chain.

The challenge is to decide where to draw the line as we move upstream and farther outside of the steel mill. We have included iron and coal mining operations, pellet production, flux mining, and zinc mining as these are key inputs. But should we include the inputs that are required to execute the pellet production process? Fuels are consumed, but they are not part of the plant's optimization function, i.e. the cost of upstream inputs is accounted for in the price of the product purchased. In essence, what processes do we exclude? The answer to this question can be based on a variety of arguments, but sophisticated arguments were not necessary to reach a conclusion. This is due to the fact that the LCA documentation does not permit further upstream analysis or inclusion. Although items such as "2237-Fuel Oil Produce/Deliver" is itemized as an input to several processes, there is no corresponding input/output/emission profile for this process, hence we cannot include it directly. This forces a different approach.

When we examined our model's performance in replicating LCA total emission figures by source, we found our model was quite accurate in all respects, but slightly underestimated emissions for these five upstream processes which rely on inputs like "2237" above, where no input/output/emission profiles are available. Therefore, based on final delivered quantities in the hypothetical case, we adjusted the emission coefficients on these five processes slightly upward in order to calibrate the model based on the total emissions reported in SCSi (1998, p. 29-30).

The external electricity generation emission profile for the Middle Atlantic region is calculated based on the LCA report. The Rhodes report provided a basis for estimating emissions per kilowatt of purchased electricity

New Technology

New technology is represented in the model as process options. For example, the model allows two different types of coke production: conventional by-product coking and non-recovery cokemaking. Several different kinds of iron technologies are available: Corex and two coal and three gas-based DRI technologies. To absorb any possible DRI production, the model allows switching from basic oxygen steel furnaces to five different EAF furnaces, each with different DRI-scrap blends. Similarly, the electricity co-generating plants have the option of using by-product gases or purchased natural gas.

Some emissions coefficients for the new technologies were estimated due to incomplete survey results. New technologies are relatively early in their development, and process coefficients varied among data sources and specific and proposed installations. We have attempted to reconcile these variations and the coefficients sometimes represent averages, estimates, and interpolations. We believe that we have achieved an accurate accounting of the input, output, and emission profiles of the new technologies. The new technologies include electric arc furnaces, non-recovery cokemaking, and direct iron reduction.

In order to constrain the addition of new technologies to reasonable levels, a set of capital constraints were added. Each new technology is assigned a lump sum capital cost in a price table. These capital costs are taken from Considine *et al.* (1992). The plant can be constrained to a fixed amount of total capital outlay (say \$500 million over the planning horizon). But these costs are not incurred as lump sums, instead we assume they are financed by some combination of debt and equity, and we amortize payments to these sources based on a twenty year life and a average cost of capital of ten percent in the base case. Costs must be amortized and included in this manner to support the structure of the optimization of annual operating costs.

Electric Arc Furnaces

Obviously, electric arc furnaces (EAF) are not new but they do represent an alternative not employed in the existing plant. Moreover, EAFs can be fed different ratios of scrap and directly reduced iron depending upon the relative cost these two materials. Data by Barnett for the Crawfordsville plant operated by Nucor, Inc. provide the labor, energy, and materials requirements for the EAF options. Emissions are based upon those presented above. Direct CO and CO₂ emissions are assumed to be negligible. The range of the PM₁₀ coefficient was very large, and using an average has significant impacts in a social planning context. A figure of 0.05 was used in consideration of BF and BOF coefficients.

To permit evaluation of different input ratios of scrap and DRI, multiple EAF processes are included in the model to represent the different fixed input ratios. An analysis was made of the effect of the input ratio of these two items has on other factors, mainly electricity consumption. There are many important factors that affect the amount of energy consumption in the EAF as a function of percent DRI charged. Some of these include:

- Physical form of the DRI (particle size)
- Friability (leads to excess fines and yield decline)
- Temperature of the DRI charge
- Batch versus Continuous Charging
- Composition (unreduced iron oxides, FeO)
- Gangue (mainly silica and alumina)

We assume continuous charging at low-medium charge rates of 10-40%. Batch charging generally leads to lower productivity, while continuous charging generally leads to improved productivity (Stephenson, 1980). The inclusion of DRI in the EAF charge may affect electricity consumption positively or negatively based on the relative influence of the factors itemized above, it is the net effect that is important for this study.

As described in Stephenson (1980, p. 110), "continuous charging of DRI results in several improvements in the melting process which tend to lower power consumption and help offset the detrimental effects of DRI composition. The improvement in power consumption occurs at relatively small additions, in the range of 10 to 30 percent of the charge, where savings

Figure 5. Electricity consumption per percent DRI charged

Source: Approximation based on Stephenson (1980, p. 110 and Figure 8-11, p. 110)

in power consumption of 3 to 10-percent have been reported when the optimum quantity of DRI is used. When more than 30 percent DRI is continuously fed, the overall effect is toward increased power consumption relative to an all scrap charge. With DRI constituting 60-75 percent of the charge, the electric power consumption experienced by most commercial DRI users is in the range of 550-650 kwh ton tapped." An approximation of this relationship is depicted in Figure 1.

The electricity consumption coefficients applied in the process model are based on Figure 1. It is important to note that in addition to the factors mentioned above regarding sensitivity of energy requirements, other items such as electrode, oxygen, and lime consumption may go up or down. Also, yields may vary as well. In order to keep the model concise, and for lack of scientific description of the complex interrelationships of these factors, none of these other factors have been accounted for in the EAF profiles.

Non-Recovery Cokemaking

The non-recovery cokemaking process involves coking, flue-gas desulfurization, and power generation. The input data are updated from the study by Considine *et al.* (1992), collected from plant operators. Steam output can be used downstream in the BF, since the Jewell process does not require steam as an input and we typically consider conventional by-product and Jewell to be mutually exclusive. Emissions are based upon Table 1 above by adding emissions from charging, coking, pushing, and quenching to calculate a total emission (averaging where needed). Polyaromatic hydrocarbon (PAH) were not included as a new due to high uncertainty of this emission coefficient. Power generation emissions are estimated based upon the previously discussed unit emissions for the existing power plants. PM10 emissions are estimated from the by-product coking emissions coefficients. Finally, our coefficients assume that all CO and CO₂ emissions from Jewell are in the offgas stream, which are emitted during the power generation process.

Direct Reduction

The first direct reduction process includes COREX. The resource requirements are from Considine *et al.* (1992) Unlike conventional blast furnaces, COREX, requires iron ore not pellets and can accept a wide range of coal types, including steam coal. Emissions are based upon Table 2 above except that CO emissions are estimated based upon the blast furnace coefficient and coal consumption.

The unit resource requirements for the remaining direct reduction technologies are based upon Table 3 above. For the Circofer process, CO, NO_x, and PM10 emissions are based on Corex coefficients, using coal as a reference. The CO₂, Slag, Phenol, Cl, and NH₃ emissions are from the manufacturer. Unit methane emissions are an average of the other DRI technologies. The CO₂ emissions coefficient for the Circored process is from estimates by the technology vendor. NO_x and PM10 coefficients are based upon two other natural gas based processes, Midrex and HYLIII processes for which data are available. Emissions of CO, SO_x, NO_x, PM10, and CH₄ by the coal-based Fastmet process are estimated based upon Circofer's unit coal consumption. CO₂ emissions from the HYLIII and Midrex process are estimated based upon the unit gas consumption of the Circored process. The process emissions coefficients for PM10, SO_x,

NO_x and CO are very close to those from a DRI plant permit application in Convent Louisiana in 1997. VOC and dust figures were taken from the permit and added to the emission profile for all five DRI processes.

Reduction gases are produced on site in a gas reformer. Reducing gases are generated from a mixture of natural gas and recycled top gas from the reduction furnace. The thermal efficiency of the reformer is enhanced with a heat recovery system. Sensible heat is recovered to preheat the combustion air used in the reformer burners and the mixture of top gas and natural gas fed to the reformer.

The majority of the top gas from the reduction furnace is recycled either for reinjection to the furnace (after cleaning) or for heat recovery. In addition, top-gases are consumed within the plant in a variety of other utilities services such as steam generation, electricity generation, and other power and preheating activities. In this analysis, we assume that all such utilities are required components of the DRI module as a whole. That is, these off-gases cannot be exported to other uses within an integrated production process. What we are concerned with are those excess gases, however small, that are available for export and their respective heat values. But due to the variety of arrangements of reformer, furnace, and utilities, one cannot know the amount of off-gas available for export without a detailed schematic of a plant. Estimates of export gas heat values are equally elusive due to changes in heat value, pressure, and temperature as top-gases pass through a maze of reuses.

Multiple technical sources were explored, yielding a few, wide ranging estimates for export gas volume and heat values. For gas-based processes, estimates ranged from 1.188 mmBTU/ton metal to 5.840 mmBTU/ton metal, depending on the particular plant schematic. For gas-based DRI processes, this study assumes 2.5 mmBTU off-gas / ton Fe and 0.5 mmBTU / ton Fe for coal-Based DRI processes. The gas-based figure compares with a figure of 4mmBTU/ton metal exported from the Blast Furnace. In the present model, the Blast Furnace similarly recycles much of its top gas, and is actually a net electricity producer. Unfortunately, we do not have such detailed information on the utilities of the DRI module, perhaps it too could be a net electricity producer.

Natural Gas Shadow Processes

Since we have adopted an aggregated coking process, coke oven gas cannot be produced without making coke, contrary to the LCA approach described above. Therefore, the model is sensitive to the availability of coke oven gas for downstream consumption within the plant. That is, if insufficient coke oven gas is available, downstream processes cannot run (note: in an input/output model such as this, there is no flexibility for substitution). To enable substitution to an alternate energy source when coke oven gas is short in supply, several processes had to be created to permit the consumption of natural gas instead. We have called these modified processes shadow processes, for they are identical to their namesakes, except for the fact that they use natural gas instead of coke oven gas. Note, making the switch to the shadow process permits the model to run, but it does come at a cost since natural gas must be purchased whereas off-gases are by-products. We assume this conversion is technically feasible and costless in the long run.

Model Calibration

The LCA study did not include the emissions associated with the production of the excess coke but did include those emissions associated with the production and use of the excess coke oven gas. In other words, the LCA treated coke and coke oven gas as two separate products rather than joint products. This is technically infeasible because the downstream processes, such as the blast furnace, utilize the coke oven gas generated by the excess coke production. Nevertheless, the LCA accounting is accurate because the eventual end users of the excess coke would count the associated emissions from its production, although they would double-count the coke oven gas under LCA's separate process approach. To ensure technical feasibility, our model solution for comparison with the LCA study produces no excess coke for sale. This results in a shortage of coke oven gas for this particular plant configuration. To attain a technically feasible solution, the model includes natural gas as a substitute fuel in iron production and other downstream processes, such as electric power generation.

Model calibration involved a careful comparison of our estimated emissions levels with the life cycle inventory data. The baseline model solution comes very close to the actual cost performance of the plant. The LCA study by Rhodes, et. al. (2000), however, is for a hypothetical output mix of totally galvanized steel. Using this output slate and the LCA emissions coefficients implied by their study, our process model replicates their emissions levels in most cases within five percent. The differences arise from slightly different input-output coefficients implied by the Barnett's data with those implied by the LCA study.

The original treatment of the coking process and the generation of coke oven gas was contained within one process in the process model. But in the LCA model, the treatment is quite different and encompasses three distinct processes. A graphical interpretation of the LCA treatment is shown in Figure 2.

The LCA analysis lists a complete input/output profile for the COPP process, but only gives one input and one output for the COGP and COKE-SLOT processes. This implies that the plant can produce coke oven gas without producing coke, and two, the plant can produce coke without producing coke oven gas. This formulation causes a large difference in coke oven gas production between the two models, since the original model does not allow independent production of coke and coke oven gas. In the original model, there cannot be one of these outputs without the other. As a result, in the LCA base case where the plant produces excess coke for merchant sales, there is no excess coke oven gas production.

In the LCA model's base case (4.586 mm tons coke production), coke oven gas production (COG) is set equal to calculated consumption. The implied net coke to gas production ratio from this assumption is 5.4174 mmBTU COG/ton coke. But in the hypothetical case with only 1.005 mm tons of coke production, coke oven gas is calculated similarly based on downstream COG fuel requirements, resulting in an implied net coke oven gas to coke production ratio of 17.1411 mmBTU COG/ton coke. This juggling of process levels and implied COG ratios is required due to the downstream COG fuel requirements in the hypothetical case. That is, if the lower COG output ratio of the base case were used in the hypothetical case, there would not be enough COG production to meet downstream COG requirements, the plant would

MATHEMATICAL STATEMENT

The model is a cost minimization problem. The analysis below considers two different measures of cost. Total private costs include the sum of variable input costs and capital charges for new investments less credits for byproduct sales. The second cost definition includes total private costs and the environmental damages associated with emissions, which we define as total social cost. The estimates of the environmental damages per unit of emissions are from a survey the environmental economics literature conducted by Newell (1998). The objective function is defined as follows:

$$C = \sum_{r=1}^{33} p_r u_r + \sum_{p=1}^{44} c_p z_p + \delta \sum_{e=1}^{37} p_e \sum_{p=1}^{44} A_{ep} z_p - \sum_{b=1}^3 p_b \sum_{p=1}^{44} A_{bp} z_p, \quad (1)$$

where C is cost, p_r and u_r represent the price and consumption levels for purchased input r , including labor, energy, and materials; $c_p z_p$ symbolize prices and purchases of new equipment, $A_{ep} z_p$ are the unit emission coefficients and process levels, and the last term measures by-product credits for two types of slag products and elemental sulfur. The private cost objective holds when $\delta = 0$ and social cost when $\delta = 1$.

The first constraint requires that production of the six products for shipment must be at least as great as market demands:

$$\sum_{p=1}^{44} A_{fp} z_p \geq x_f, f = 1, \dots, 6, \quad (2)$$

where A_{fp} are technical coefficients. The products include coke, cold rolled band, hot-dipped galvanized, and three types of hot rolled band. The next set of constraints ensure that intermediate products supplied by upstream plants are at least as large the demand for them downstream:

$$\sum_{p=1}^{44} A_{ip} z_p \geq 0 \quad i = 1, \dots, 27. \quad (3)$$

Note that elements of A_{ip} , the technical coefficients for intermediate products, are negative for inputs and positive for outputs. A strict equality holds for coke oven and blast furnaces gases because these gases cannot escape for environmental reasons. Raw material balances require that purchases equal demand for inputs by the plant:

$$\sum_{p=1}^{44} A_{ip} z_p + u_i = 0 \quad i = 1, \dots, 33, \quad (4)$$

where A_{rp} are unit resource requirements. Equipment capacities also constrain plant production activities:

$$\sum_{p=1}^{44} B_{mp} z_p \leq k_m \quad i = 1, \dots, 44, \quad (5)$$

where B_{mp} are zero-one coefficients that link plant activities with equipment. For example, the blast furnace activity requires blast furnace capacity.

CHAPTER VI: MODEL SIMULATION RESULTS

In addition to providing guidance on policy analysis and planning issues, the above model provides a convenient accounting tool for comparing the economic and environmental performance of alternative steel production technologies. To conduct such a comparison, we set capacity constraints to force the model to calculate costs and emissions for five technologies:

1. integrated steel production,
2. nonrecovery coke ovens,
3. Corex iron production
4. 100% scrap based electric arc furnace production
5. Scrap & DRI electric arc furnace production.

Integrated steel production with no excess coke production constitutes the base case. Combined production of the five steel products equals 2.546 million tons per year of galvanized steel sheet. These simulations also assumed that there are no purchases of coke, hot-rolled band, steel slabs, and directly reduced iron. Although many plants make such purchases, allowing such flexibility would skew the basis of comparison. The objective function used in the following section is the minimization of private cost.

BASELINE TECHNOLOGY COMPARISONS

A comparison of energy and material use for these five technologies appears in Table 6. The first notable difference is that electricity consumption for the EAF technologies are nearly five times higher than integrated steel production. The Jewell and Corex plant configurations consume less purchased electricity than the base case because they generate larger amounts of electricity than the integrated plant. In fact, Corex consumes 25 percent less electricity than the conventional integrated steel plant. On the other hand, Corex involves nearly a six-fold increase

Table 6: Comparison of energy and material use for alternative steel technologies

	<u>Base Case</u>	<u>Jewell</u>	<u>Corex</u>	<u>Scrap EAF</u>	<u>Scrap & DRI EAF</u>
Energy					
Coal (million tons)	1.6	1.6	2.4		
Electricity - mkwh	391.5	320.8	219.4	1,979.3	1,885.1
Energy - Other (mmbtu)	1.2	1.2	1.2	1.6	1.6
Natural Gas (bcf)	19.1	18.6	10.3	10.0	19.9
Materials					
			<u>tons</u>		
Flux	157,000	157,000	75,000		
Iron Ore / Pellets	3,291,000	3,291,000	3,498,000		1,578,000
Oxygen	348,000	348,000	1,988,000	121,000	121,000
Scrap Iron & Steel	756,000	756,000	576,000	2,886,000	1,897,000

in oxygen consumption and consumes less scrap consumption than the base case. Naturally, the scrap based EAF does not use metallurgical coal or iron ore. It also consumes substantially less oxygen than the base case. The scrap DRI plant configuration uses about 54 percent scrap and more natural gas than the base case.

The emissions profile associated with these technologies appear in Table 7. Very small water emissions are not reported, although they are included in social cost. Conventional integrated steel production generates 10.4 million tons of emissions. This translates to almost 4.1 tons of emissions per ton of finished product. More than 65 percent of emissions are carbon dioxide from fuel combustion. The next largest emission is solid waste, comprising 23 percent of total emissions, from mining overburden, such as from open pit iron mining. Another 9.5 percent is slag, which is now a marketable by-product in the steel industry. The other 2.5 percent of emissions by weight include largely methane, nitrogen, and sulfur compounds

Table 7: Air and solid wastes emissions from alternative steel technologies in tons

	<u>Base Case</u>	<u>Jewell</u>	<u>Corex</u>	<u>Scrap EAF</u>	<u>Scrap & DRI EAF</u>
Air Emissions					
CH ₄	70,742	69,994	126,845	46,186	45,143
CO	4,143	3,890	4,493	1,306	1,809
CO ₂	6,786,136	6,595,641	10,176,629	3,921,018	5,328,065
DUST	7,470	9,184	6,717	10,704	12,194
HC	766	634	653	634	663
HCL	190	180	178	310	345
HF	7.0	6.5	6.5	10.0	12.0
NO _x	16,865	15,008	13,799	29,598	31,197
ORG	141	127	125	0	56
PM10	1,309	1,305	810	110	173
SO _x	15,968	15,416	13,133	21,146	22,774
Solid Wastes					
MIN-WASTE	2,390,100	2,393,560	2,749,758	174,751	1,013,413
MIXED	9,973	9,981	10,539	8,956	8,975
SLAG-ASH-I	628,251	628,251	966,539	0	130,187
SLAG-ASH-S	361,932	361,932	361,932	399,633	399,633
SLAG-ASH-W	26,391	25,287	21,884	32,298	36,113
SLUDGE	63,286	63,286	126,571	99,532	128,626
SULFUR-E	0	5,380	0	0	0
Total Emissions*	10,383,666	10,199,060	14,580,608	4,746,189	7,159,376
* Includes a small amount of water emissions.					

The Jewell process generates slightly less total emissions than integrated production because purchased electricity is lower because the non-recovery ovens generate relatively more

off-gases for electricity co-generation. Even though Corex generates more electricity, iron ore and coal consumption are substantially higher, which generate greater amounts of solid waste and significantly higher levels of CO₂ emissions. Unit emissions for Corex are 14 percent higher than integrated steel production using conventional coke ovens and blast furnaces. The two scrap using technologies generate substantially lower emissions, on the order 1.9 tons and 2.8 tons per ton of finished steel output, representing 34 and 16 percent reductions respectively from conventional integrated steel production. In addition to reductions in solid waste since virgin ores are not consumed, there are significant reductions in CO₂ emissions for these two EAF options. Dust, sulfur oxide, and nitrogen oxide emissions, however, are substantially higher than the base case. In terms of mass, the scrap-based technologies generate substantially lower emissions than virgin material based production.

The incremental costs of the four options to integrated steel production are listed in Table 8. The scrap steel based technologies have slightly lower operating costs than the base case. Operating costs for Jewell are slightly more than one percent higher and those for Corex are more than 5 percent higher than the base case. Using the unit emissions charges collected by Newell (1998) and the emission levels from Table 2, Table 3 presents environmental damage costs. Surprisingly, total environmental costs for the scrap-based technologies are higher than the base case. The benefits of foregone CO₂ emissions are more than offset by higher societal costs associated with emissions of dust, sulfur oxides, and nitrogen oxides.

CARBON TAX POLICIES

Carbon taxes are a common concern of many steel companies and government policy makers allocating research and development resources. An analysis of steel technology choice under various carbon taxes appears in Table 4. The alternative carbon taxes are on purchased fuels based upon their carbon content. As Table 9 indicates, assuming private cost minimization, the optimal plant configuration in the base case under no carbon taxes consumes both scrap and directly reduced iron. As carbon taxes increase under private cost minimization, scrap consumption rises.

The social cost minimization solutions also appear in Table 9. Notice that the integrated mill is optimal under the base case that minimizes social cost. Private costs are higher but environmental damage costs are considerably lower, which lowers total social costs. As carbon taxes rise, scrap consumption also rises but only at higher carbon tax rates.

Table 8: Incremental costs for new steel technologies (millions of dollars)

Private Costs	<u>Jewell</u>	<u>Corex</u>	<u>Scrap EAF</u>	<u>DRI & Scrap</u>
<i>Labor & Misc.</i>				
Labor & Maintenance	5.8	24.0	-124.7	-100.6
New Capital - Amortized	25.5	67.6	51.4	74.6
Other	-9.7	-16.6	-26.4	-22.8
<i>Energy</i>				
Coal - Coke	1.0	37.4	-68.9	-68.9
Electricity - Purchased	-3.5	-8.6	79.4	74.7
Energy - Other	-1.0	-1.0	2.1	2.1
Natural Gas	-1.1	-17.7	-18.3	1.5
<i>Materials</i>				
Electrodes	0.0	0.0	17.7	17.7
Flux and Metals	0.0	-7.9	-53.3	-53.3
Iron Ore & Pellets	0.0	9.7	-126.7	-65.2
Oxygen	0.0	35.9	-5.0	-5.0
Refractories	0.0	0.0	-14.9	-14.9
Scrap Iron & Steel	0.0	-21.4	297.5	160.9
Other	0.0	-17.8	-17.8	-17.8
Total private costs	16.9	83.6	-7.7	-16.8
% Change	1.04	5.15	-0.48	-1.03
Environmental Damages				
<i>Air Emissions</i>				
CH4 & CO	-0.2	14.5	-6.4	-6.6
CO2	-2.4	42.0	-35.5	-18.1
DUST	19.6	-8.6	37.0	54.0
HC, HCL, & HF	-1.5	-1.3	-1.4	-1.1
LEAD-A, NH3, & VOC	0.0	0.0	0.0	0.0
ORG	0.0	0.0	-0.2	-0.1
PM10	0.0	-5.7	-13.7	-13.0
SO _x	-6.6	-34.2	62.4	82.0
VOC	0.0	0.0	0.0	0.0
<i>Solid Wastes</i>				
MIXED	0.0	0.0	-0.1	-0.1
SLAG-ASH-I	0.0	-3.1	5.7	4.5
SLAG-ASH-S	0.0	0.0	-0.1	-0.1
SLAG-ASH-W	-0.1	-0.2	0.3	0.5
SLUDGE	0.0	3.2	1.8	3.3
SULFUR-E	-0.2	0.0	0.0	0.0
Total Environmental costs	3.6	-1.7	84.8	144.6
Total Social Costs	20.4	81.8	77.1	127.8
% Change	1.26	5.04	4.75	7.87

Table 9: Steel technology choice under various carbon taxes

<u>Private Cost Minimization</u>				
<u>Scenario</u>	<u>Operating Cost</u>	<u>Environment Damages</u>	<u>Total Costs</u>	<u>Plant Configuration</u>
Base Case	1.00	1.00	1.00	EAF4 and MIDREX for DRI
\$15 tax	1.01	0.94	0.98	EAF3, less MIDREX and more scrap
\$35 tax	1.01	0.94	0.99	EAF3, less MIDREX and more scrap
\$100 tax	1.04	0.91	1.00	EAF2, less MIDREX and more scrap
<u>Social Cost Minimization</u>				
Base Case	1.02	0.68	0.91	Integrated Mill
\$15 tax	1.04	0.69	0.92	Mixed mill
\$35 tax	1.05	0.69	0.93	EAF1, all scrap
\$100 tax	1.09	0.69	0.95	EAF1, all scrap

CHAPTER VII. POLICY IMPLICATIONS

Life cycle assessment and impact analysis are used by many industries for a variety of reasons. In the steel industry, life cycle inventory data and impact analysis provide an important benchmark to measure environmental progress and to assess environmental competitiveness with competing materials, such as aluminum, wood, and other materials. Life cycle analysis for the most part is an accounting exercise. This accounting, however, must be carefully completed within the technical boundaries of the production process. In this study, we had the unique opportunity to join an engineering-economic model of the steelmaking process with a life cycle analysis of steel production. During the course of this investigation, we discovered that the life cycle study of the steel production was technically infeasible. While this had no major bearing on the results of the life cycle analysis, it may preclude the applicability of the life cycle findings to other steel facilities. Technical feasibility is very important in steelmaking because recovery of by-product gases and materials is essential in profitably running these plants and in evaluating new process options. This suggests that technical feasibility should be a pre-condition for life cycle environmental impact analysis.

Five different plant configurations are examined in this study from conventional integrated steel production to completely scrap-based operations. Two cost criteria are used to evaluate technology choice: private and social cost, with the latter including the environmental damages associated with emissions.

On the basis of the total quantity of emissions in mass units, scrap based steel production is environmentally superior to conventional integrated steel production. Using an economic valuation of the life cycle environmental impacts, however, indicates that these two technology paths are quite similar. In fact, using conventional damage cost estimates, this study finds that electric arc furnace steel production imposes slightly greater environmental damages than integrated production due substantially greater emissions of SO_x and NO_x emissions resulting from the electricity generated to supply these facilities. Hence, adopting a life cycle perspective for technology assessment can yield some rather surprising conclusions.

This simple finding starkly highlights perhaps one of the more fundamental issues surrounding the policy relevance of the emerging field of industrial ecology: valuation and aggregation of life-cycle impacts. There is no doubt substantial controversy surrounds valuation issues. Resolution of these valuation issues is unlikely. For this study, a critical valuation issue for steel technology choice involves how society values environmental damages associated with solid waste and CO_2 emissions from integrated steel production versus the SO_x , NO_x , and dust from the generation of electric power used by minimills. Further analysis of this issue should be cast in a stochastic framework, which would quantify the sensitivity of these findings to prices for scrap and natural gas and to other key assumptions.

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APPENDIX A: ELECTRICITY BALANCE

Table A1 presents a comparison of the electricity balance based upon the LCA Model's base case (SCSI, 1998, p. 17-18) and the process model.

Table A1: Comparison of Electricity Consumption in Base Case

SCSI (1998, p. 17-18)				Process Model			
Process	Coeff.	Process Level	kW-h	Coeff.	Process Level	kW-h	Process
Coking	-126.0000	4,586	-577,856	-4.7778	157,645	-753,193	COPP
COG Prod. (1)(2)		39,688	-189,554				
By-products (2)		15,076	-75,801				NA
Power plant #1			206,508	0.0253	8,168,000	206,487	POWER1
Blast Furnace (net)	93.2000	2,234	208,219	93.2000	2,222	207,090	BF
BOF	-101.0000	2,803	-283,135	-101.0000	2,910	-293,910	BOF
Cont. Casting/Cutting	-24.8000	2,803	-69,522	-20.0000	2,825	-56,500	CAST-CCS
Power plant #2a (net)			151,797	0.0449	10,405,000	467,455	POWER2
Power plant #2b (net)			149,310				
Power plant #2c (net)			148,214				
Hot Strip Mill	-99.5000	2,641	-262,807	-99.0000	2,716	-268,884	HRB
Pickling	-9.1000	1,439	-13,091	-9.0000	1,737	-15,633	HRB-PICKLE
Cold Rolling	-88.6000	1,236	-109,506	-141.0000	1,569	-221,229	CR-TANDEM
Ann. & Temper	-52.1000	840	-43,790	-30.0000	1,165	-34,950	CR-BA
				-30.0000	0	0	CR-CA
				-40.0000	1,115	-44,600	CR-TFINISH
HD Galv.	-33.1000	265	-8,756	-33.0000	385	-12,705	GAL-HD
Power plant #3			n/a-steam only				
TOTALS			-779,771			-820,571	

(1) COG Gas production manually set to equal consumption.
 (2) Origin of electricity coefficient is unknown.

As is evident in the table, the two models do not necessarily produce the same estimate of purchased electricity. The LCA model includes by-product production, which apparently is inconsistent with the process levels of cokemaking or coke oven gas production. In the second case of imbalance associated with the cold rolling processes, it appears that the difference is due to the fact that the process model accounts for more distinct cold rolling process, or that the electricity input coefficient for CR-TANDEM activity is significantly higher than the comparable process in the LCA model. Comparisons change as a function of the specific case being run, but in all cases we have run to date, the electricity consumption is consistently in the neighborhood of the LCA totals.

APPENDIX B: PROCESS UNITS

<u>Process Name</u>	<u>Description</u>
BF	Blast Furnace
BF-NG	Blast Furnace - Natural Gas Based
BOF	Basic Oxygen Furnace
BOF-NG	Basic Oxygen Furnace - Natural Gas Based
CAST-CCS	Continuous Casting of Slabs
CCOALP	Coal Mine (external)
CFER	Circofer DRI Process
COKE-SLOT	Slot Oven Cokemaking
COREX	Corex DRI Process
CR-BA	Cold Rolled Band, Batch Annealing
CR-CA	Cold Rolled Band, Continuous Annealing
CR-TANDEM	Cold Rolled Band, Tandem and Cleaned
CR-TANDEM-NG	Cold Rolled Band, Tandem and Cleaned - Natural Gas Based
CR-TFINISH	Cold Rolled Band, Tempered and Finished
CRED	Circored DRI Process
EAF(i)	Electric Arc Furnace
ELECP	Externally Purchased Electricity (external)
FASTMET	Fastmet DRI Process
FLUX-MINE	Flux Provision Process (external)
GAL-HD	Hot Dip Galvanizing
HRB	Hot Rolled Band
HRB-NG	Hot Rolled Band - Natural Gas Based
HRB-PICKLE	Hot Rolled Band, Pickled
HRB-TFINISH	Hot Rolled Band, Tempered and Finished
HYLIII	HylIII DRI Process
IRON-MINE	Iron Mine (external)
JEWELL	Jewell DRI Process
MIDREX	Midrex DRI Process
PCI	Pulverized Coal Injection
PCOKE	Purchased Coke Process
PDRI	Purchased DRI Process
PEL-MINE	Pellet Mine (external)
PFGD	Flue Gas Desulfurization (Jewell)
PGEN	Utility Power Plant (Jewell)
PGEN-NG	Utility Power Plant (Jewell) - Natural Gas Based
PHRBAND	Purchased HRBAND Process
POWER(i)	Internal Power Plants
POWER(i)-NG	Internal Power Plants - Natural Gas Based
POWER2-CRX	Power Plant - BFG Based
PSCRAP-STEEL	Purchased Scrap Process
PSLABS	Purchased Slab Process
SCREEN	Coke Screening
SINTER	Sintering of Iron Ore
VDG	Vacuum Degasser
ZINC-MINE	Zinc Mine (external)

APPENDIX C: COMMODITIES

The following table of commodities includes raw and intermediate inputs and final products (marked with an asterisk). Items not named as purchased can be assumed to be intermediate. Prices in the process code are per these units.

Commodity Name	Description	Units
BREEZE	Coke Fines	xxxxxx
COAL-COKE	Coking Coal	TON
COAL-COKEP	Purchased Coking Coal	TON
COAL-STEAM	Steaming Coal	TON
COKE*	Unscreened Coke	TON
COKEP	Purchased Unscreened Coke	TON
COKE-BF	Blast Furnace Coke, Screened	TON
CRBAND-BA	Cold Rolled Band, Batch Annealed	TON
CRBAND-CA	Cold Rolled Band, Continuous Annealed	TON
CRBAND-TC	Cold Rolled Band, Tandem and Cleaned	TON
CRBAND-TF*	Cold Rolled Band, Tempered and Finished	TON
DRI	Directly Reduced Iron	TON
DRIP	Purchased Directly Reduced Iron	TON
ELECTRIC	Electricity	KWH
ELECTRICP	Purchased Electricity	KWH
ELECTRODES	Electrodes	LBS
ENERGY-OTHER	Other Energy	MMBTU
FLUX	Major Fluxes (limestone, lime, etc.)	TON
FLUXP	Purchased Major Fluxes (limestone, lime, etc.)	TON
FLUX&METALS	Misc Fluxes, Flourine, Aluminum, and Other Metals	\$
FUELOIL	Fuel Oil	BBLS
GASOLINE	Gasoline	BBLS
HD-GALV*	Hot Dipped Galvanized Band Steel	TON
HRBAND*	Hot Rolled Band	TON
HRBANDP	Purchased Hot Rolled Band	TON
HRBAND-PCL*	Hot Rolled Band, Pickled	TON
HRBAND-TF*	Hot Rolled Band, Tempered and Finished	TON
IRON-LIQ	Liquid Iron	TON
IRON-LIQ-DS	Liquid Iron, Desulphurized	TON
IRON-ORE	Lump Iron Ore	TON
IRON-OREP	Purchased Lump Iron Ore	TON
IRON-PEL	Iron Pellets	TON
IRON-PELP	Purchased Iron Pellets	TON
LABOR-D	Direct Labor	MAN HOURS
LABOR-I	Indirect Labor (M&MH)	MAN HOURS
LIQUOR		\$

Continued...

Commodity Name	Description	Units
MAINT	Operations and Maintenance	\$
NAT-GAS	Natural Gas	MCF
NITROGEN	Nitrogen and Hydrogen	\$
OFFGAS-B	Blast Furnace Gas	MMBTU
OFFGAS-C	Coke Oven Gas	MMBTU
OPCOST	Nonspecific Operating Costs and Supplies	\$
OXYGEN	Oxygen	TON
PCI	Pulverized Coal Injection	TON
PCI-LEASE	Pulverized Coal Injection, Lease / Finance Costs	\$
REFRACTORIES		\$
ROLLS		\$
SCRAP-IRON	Pig Iron Scrap	TON
SCRAP-STEEL	Steel Scrap	TON
SCRAP-STEELP	Purchased Steel Scrap	TON
SINTER	Sinter	TON
SINTER-FEED	Sinter Feed (Iron Ore Fines)	TON
SLABS	Steel Slabs	TON
SLABSP	Purchased Steel Slabs	TON
SLAG-ASH-I	Ironmaking Slag (sellable)	TON
SLAG-ASH-S	Steelmaking Slag (sellable)	TON
SSD-B		
SSD-S		
STEAM(i)	Steam Output from ith Power Plant	MJ
STEEL-LIQ	Liquid Steel	TON
STEEL-LIQ-VDG	Liquid Steel, Vacuum Degassed	TON
SULFUR-E	Elemental Sulfur (sellable)	TON
TRANSPORT		
WIND		
ZINC	Zinc	TON
ZINCP	Purchased Zinc	TON

APPENDIX D: EMISSIONS IN THE PROCESS MODEL

All units are pounds. Prices in the model are per pound emitted/disposed.

<u>Emissions</u>	<u>Description</u>
AL	Aluminum
AMMONIA	Ammonia
BOD	Biochemical Oxygen Demand
CH ₄	Methane
CL	Chlorine
CN	Cyanide
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DET-OIL	Detergent and Oils
DISS-ORG	Dissolved Organics
DUST	Dust, >PM10
FE	Iron
HC	Hydrocarbons
HCL	Hydrochloride
HF	Hydroflouride
LEAD-A	Lead - Airborne
LEAD-W	Lead - Waterborne
METAL	Metals
MIN-WASTE	Mining Spoils
MIXED	Mixed Industrial Waste
MIN-WASTE	Mineral Wastes
MIXED	Mixed Wastes
NH ₃	
NH ₄	
NO ₃	
NO _x	
ORG	Organics
PHENOL	Phenol
PM10	Particulate Matter, <10microns
SLAG-ASH-W	Slag and Ash - Waste (not sellable)
SLUDGE	Sludge
SO _x	
SS	Suspended Solids
SULFUR-W	Sulfur - Waste (not sellable)
VOC	Volatile Organic Compounds
ZN	Zinc