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AVAILABLE AND EMERGING TECHNOLOGIES FOR REDUCING GREENHOUSE GAS EMISSIONS FROM THE IRON AND STEEL INDUSTRY

Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry

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Abbreviations and Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
AC	alternating current
ACCCI	American Coke and Coal Chemicals Institute
AISI	American Iron and Steel Institute
AIST	Association for Iron & Steel Technology
Al_2O_3	aluminum oxide
ANSI	American National Standards Institute
AOD	argon-oxygen decarburization
BACT	best available control technology
BFG	blast furnace gas
BOF	basic oxygen furnaces
Btu	British thermal unit
CaO	calcium oxide
CCAP	Center for Clean Air Policy
cm	centimeter
CCS	carbon capture and sequestration
CHP	combined heat and power
CFD	computational fluid dynamics
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
COG	coke oven gas
DC	direct current
DOE	United States Department of Energy
DRI	direct reduced iron
EAF	electric arc furnaces
EMS	energy management systems
EPA	United States Environmental Protection Agency
FeO	iron oxide
Ft	feet
ft^3	cubic foot
g/m^3	grams per cubic meter
GHG	greenhouse gas
GJ	gigajoule
gr/ft^3	grains per cubic foot
hr	hour
in	inch(es)
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
kg	kilogram

kVA	kilovolt amps
kWh	kilowatt hour
lb	pounds
m	meter(s)
m^3	cubic meter
MMBtu	million British thermal units
MgO	magnesium oxide
mm	millimeters
NO_x	nitrogen oxide
PM	particulate matter
$PM_{2.5}$	particulate matter with a diameter less than 2.5 micrometers (10^{-6} m)
PSD	prevention of significant deterioration
PSH	paired straight hearth
R&D	research and development
scf	standard cubic feet
SiO_2	silicon dioxide
SOx	sulfur oxide
ton	ton (short, English)
tonne	metric ton (equal to 1.102 short tons)
tpy	tons (short) per year
UHP	ultra-high power
ULCOS	ultra-low CO_2 steelmaking
U.S.	United States
VSD	variable-speed drive
yr	year

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I. Introduction

This document is one of several white papers prepared by the United States Environmental Protection Agency (EPA) that summarize readily available information on control techniques and measures to mitigate greenhouse gas (GHG) emissions from specific industrial sectors. These white papers are solely intended to provide basic information on GHG control technologies and reduction measures to assist States and local air pollution control agencies, tribal authorities, and regulated entities in implementing technologies or measures to reduce GHGs under the Clean Air Act, particularly in permitting under the prevention of significant deterioration (PSD) program and the assessment of best available control technology (BACT). These white papers do not set policy, standards or otherwise establish any binding requirements; such requirements are contained in the applicable EPA regulations and approved state implementation plans.

II. Purpose of this Document

This document provides information on control techniques and measures that are available to mitigate greenhouse gas (GHG) emissions from the Iron and Steel manufacturing sector at this time. Because the primary GHG emitted by the Iron and Steel industry is carbon dioxide (CO_2), the control technologies and measures presented in this document focus on this pollutant. While a large number of available technologies are discussed here, this paper does not necessarily represent all potentially available technologies or measures that that may be considered for any given source for the purposes of reducing its GHG emissions. For example, controls that are applied to other industrial source categories with exhaust streams similar to the Iron and Steel sector may be available through “technology transfer” or new technologies may be developed for use in this sector.

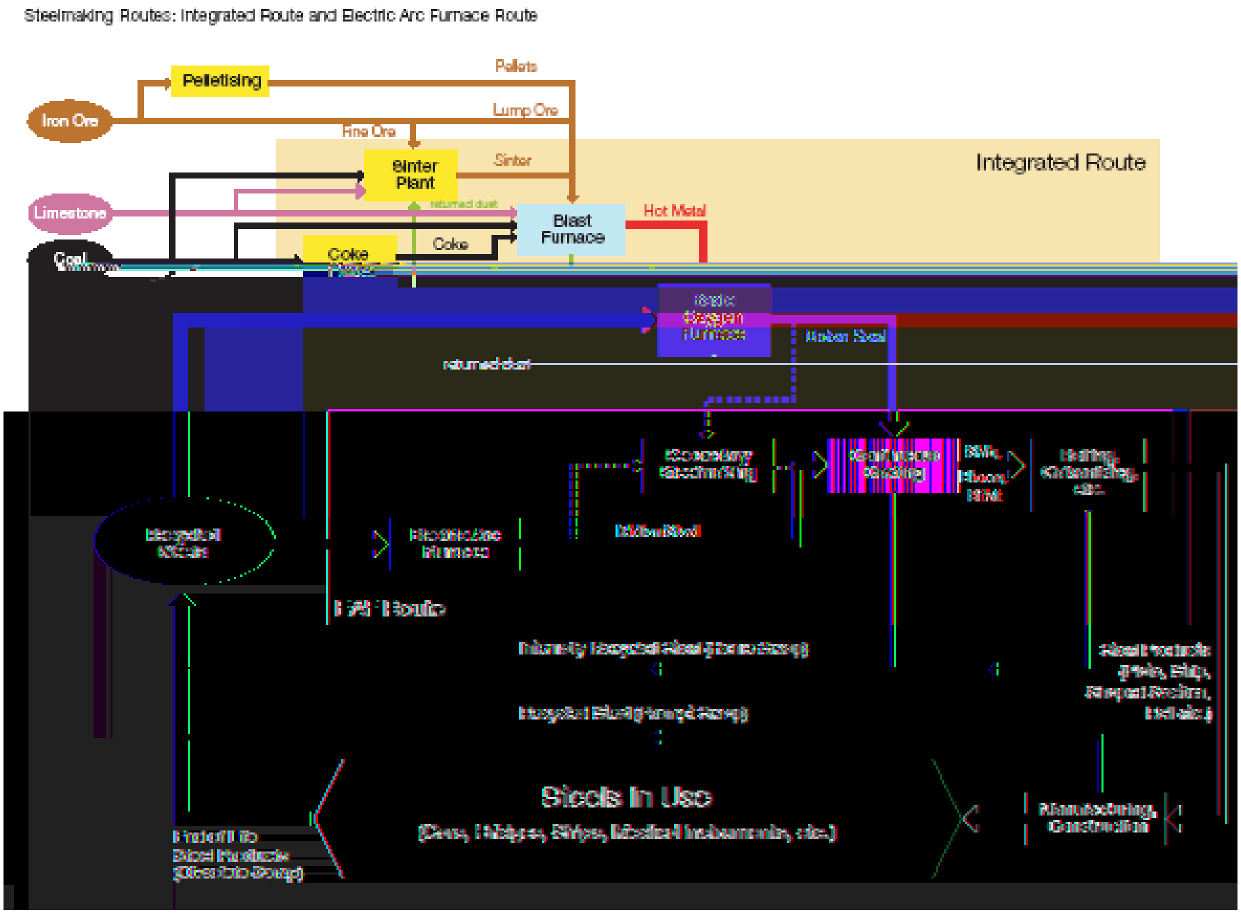
The information presented in this document does not represent EPA endorsement of any particular control strategy. As such, it should not be construed as EPA approval of a particular control technology or measure, or of the emissions reductions that could be achieved by a particular unit or source under review. This revised version reflects changes made as a result of comments submitted to the EPA.

III. Organization of This Document

This document begins with a brief description of the Iron and Steel industry below (section IV) and then is followed by a discussion Energy Programs and Management Systems (section V), including both formal programs and the steel industry’s own initiatives. A summary of GHG control measures follows (section VI) that includes those measures that have been performed on various scales, from single facilities to whole industry sectors. Technical details of energy efficiency measures at specific industry processes follow in section VII. The references used in this document are in section VIII. **Appendix A** reports on some emerging techniques for GHG control. **Appendix B** includes a list of Iron and Steel facility locations and sizes (as of the date of this document), and historic energy intensity in the industry from 1950 through 2006. In **Appendix C** are details of the energy costs and savings that were discussed in section VII. **Appendix D** has detailed descriptions of the various Iron and Steel processes that are briefly discussed in section IV; this appendix also includes an estimate of GHG emissions from the various sectors and processes.

IV. Description of the Iron and Steel Industry

The production of steel at an ***Integrated Iron And Steel plant*** is accomplished using several interrelated processes. The major processes are: (1) coke production; (2) sinter production; (3) iron production; (4) raw steel production; (5) ladle metallurgy; (6) continuous casting; (7) hot and cold rolling; and (8) finished product preparation. The operations for secondary steelmaking, where ferrous scrap is recycled by melting and refining in electric arc furnaces (EAF) include only (4) through (8) above. The interrelation of these operations is shown in a general flow diagram of the Iron and Steel industry in **Figure 1**.



Source: International Iron and Steel Institute

Figure 1. **Routes to steelmaking**

The GHG emissions in steelmaking are generated as one of the following: (1) process emissions, in which raw materials and combustion both may contribute to CO_2 emissions; (2) emissions from combustion sources alone; and (3) indirect emissions from consumption of electricity (primarily in EAF and in finishing operations such as rolling mills at both Integrated and EAF plants). The major process units at Iron and Steel facilities include the following:

- Sinter plant;
- Non-recovery coke oven battery combustion stack;
- Coke pushing;
- Blast furnace;
- Basic oxygen furnace (BOF) exhaust; and
- EAF exhaust.

The primary combustion sources of GHGs include the following:

- Coke oven battery combustion stack;
- Blast furnace stove;
- Boiler;
- Process heater;
- Reheat furnace;
- Flame-suppression system;
- Annealing furnace;
- Flare;
- Ladle reheater; and
- Other miscellaneous combustion sources.

For Integrated steelmaking, the primary sources of GHG emissions are blast furnace stoves (43 percent), miscellaneous combustion sources burning natural gas and process gases (30 percent), other process units (15 percent), and indirect emissions from electricity usage (12 percent). For EAF steelmaking, the primary sources of GHG emissions include indirect emissions from electricity usage (50 percent), combustion of natural gas in miscellaneous combustion units (40 percent) and steel production in the EAF (10 percent). For Coke facilities, the battery stack is the highest source with over 95 percent of the GHG emissions for recovery (by-product) Coke plants and 99 percent of the GHG emissions for nonrecovery (heat recovery) plants. Additional information on the estimated GHG emissions from the Iron and Steel sector is provided in **Appendix D**.

The following paragraphs provide brief descriptions of Iron and Steel processes. Lists of plants and locations can be found in **Appendix B**. More detailed process descriptions are provided in **Appendix D**.

Coke is the carbon product that is formed by the thermal distillation of coal at high temperatures in the absence of air in coke oven batteries. Coke is used in the blast furnace to provide a reducing atmosphere and is also a source of fuel. Most coke in the United States (U.S.) is produced in by-product recovery coke oven batteries, which recover tar, light oil, ammonia, and coke oven gas (COG) from the vapors generated in the ovens. Approximately one-third of the cleaned COG is used to fuel the coke ovens, and the balance is used in other combustion units at the steel plant. The four newest Coke plants use non-recovery coke oven batteries that burn the by-products rather than recover them. The new non-recovery Coke plants capture the waste heat from combustion to generate steam and electricity. The primary GHG emission point at Coke plants is the battery's combustion stack.

Sintering is a process that recovers the raw material value of many waste materials generated at Iron and Steel plants that would otherwise be landfilled or stockpiled. Feed material to the sintering process includes ore fines, coke, reverts (including blast furnace dust, mill scale, and other by-products of steelmaking), recycled hot and cold fines from the sintering process, and trim materials (e.g., limestone, calcite fines, and other supplemental materials needed to produce a sinter product with prescribed chemistry and tonnage). The sinter feed materials are fused together by a flame, fueled by natural gas and/or COG, plus the ignition of coal and coke fines in the sinter feed. The product is a hard-fused material called sinter that is suitable for charging to the blast furnace. The primary emissions point of interest for the sinter plant is the stack that discharges the exhaust gases after gas cleaning. The CO_2 is formed from the fuel combustion (COG or natural gas) and from carbon in the feed materials, including limestone, coke fines, and other carbonaceous materials.

Iron is produced in ***blast furnaces*** by the reduction of iron-bearing materials with a hot gas. The large, refractory-lined furnace is charged through its top with iron ore pellets (taconite), sinter, flux (limestone and dolomite), and coke, which provides the fuel and forms a reducing atmosphere in the furnace. Many modern blast furnaces also inject pulverized coal or other sources of carbon to reduce the quantity of coke required. Iron oxides, coke, coal, and fluxes react with the heated blast air injected near the bottom of the furnace to form molten reduced iron, carbon monoxide (CO), and slag. The molten iron and slag collect in the hearth at the base of the furnace and are periodically removed from the furnace ("tapping"). The blast furnace gas (BFG) is collected at the top of the furnace and is recovered for use as fuel in the blast furnace stoves and other parts of the steel plant. The vast majority of GHGs (as mostly CO_2) are emitted from the blast furnaces' stove stacks where the combustion gases from the stoves are discharged. The carbon in the CO_2 exhaust comes mostly from the coke and coal used a fuel. A small amount of emissions may also occur from flares, leaks in the ductwork for conveying the gas, and from blast furnace emergency venting.

Basic oxygen furnaces are large, open-mouthed, pear-shaped vessels lined with a basic (as opposed to acidic) refractory material that refines molten iron from the blast furnace and ferrous scrap into steel by injecting a jet of high-purity oxygen to remove carbon as CO and CO_2. The large quantities of CO produced by the reactions in the BOF are converted to CO_2 by combustion at the mouth of the furnace in BOF equipped with open hoods that draw in outside air, or by flaring after gas cleaning in BOF with tight-fitting closed hoods (called suppressed combustion). Final gas cleaning is performed by either venturi scrubbers or electrostatic precipitators for open hood BOF. However, only venturi scrubbers are used on closed hood BOF because of the explosion hazard from electrostatic precipitators if they were to be applied to the suppressed combustion gas stream that is rich in CO. The major emission point for CO_2 from the BOF is the furnace exhaust gas that is discharged through a stack after gas cleaning. The carbon in the CO_2 exhaust comes mostly from the molten iron and scrap. Carbon may also be introduced into the BOF to a much smaller extent from fluxing materials and other process additives that are charged to the furnace.

Electric arc furnaces are used to produce carbon steels and alloy steels primarily by recycling ferrous scrap. Cylindrical refractory-lined EAF are equipped with carbon electrodes that can be raised or lowered through the furnace roof. After ferrous scrap is charged, the electrodes are lowered and melting of the scrap begins when electrical energy is supplied to the carbon electrodes. Oxy-fuel burners and oxygen lances may also be used to supply chemical energy. Oxy-fuel burners, which burn natural gas and oxygen, use convection and flame radiation to transfer heat to the scrap metal. Some EAF plants, primarily the small specialty and stainless steel producers, use argon-oxygen decarburization (AOD) to further refine the molten steel from the EAF to produce low-carbon steel. In the AOD vessel, argon and oxygen are blown into the bottom of the vessel, and the carbon and oxygen react to form CO_2 and CO, which are removed from the vessel. CO_2 emissions from EAF are generated primarily during the melting and refining processes, which remove carbon as CO and CO_2 from the charge materials and carbon electrodes. The emissions from the EAF are captured and sent to baghouses for removal of particulate matter (PM).

As the hot waste gases leave the EAF, combustion air is typically introduced to the ductwork to convert the CO to CO2, since CO is a regulated criteria pollutant. This practice, called post-combustion, is widely used throughout the industry as the best technology for CO control.

Emissions of CO_2 are also generated from the use of oxy-fuel burners by EAF. These burners increase the effective capacity of the EAF by increasing the speed of the melt and reducing the consumption of electricity and electrode material, which reduces energy-related GHG emissions. Oxy-fuel burners also increase heat transfer while reducing heat losses, and reduce tap-to-tap time. These burners are often designed to minimize the increase in NOx emissions that is a known by-product of the technology by deliberately operating the burners at less than their maximum combustion efficiency; however, this practice increases CO emissions to some extent but in turn lowers CO_2 emissions. (AISI, 2011)

The steel produced by both BOF and EAF typically follow similar routes after the molten steel is poured from the furnace. The molten steel is transferred to the ladle metallurgy process where the metal chemistry is adjusted to meet the final steel product specifications, which may include adding small amounts of other metal alloys. The steel then proceeds to the continuous caster, which casts the steel into semi-finished shapes (e.g., slabs, blooms, billets, rounds, and other special sections). Steel from the continuous caster is processed in rolling mills to produce the final steel shapes that are sold by the steel mill. In most cases, these cast shapes will be cooled and stockpiled for later introduction into the rolling mill where the final market shape will be produced. These shapes include coiled strips, rails, and other structural shapes, as well as sheets and bars. Because rolling mills consume electricity, they consequently contribute to indirect emissions of GHGs. The semi-finished products may be further processed by using many different steps, such as annealing, hot forming, cold rolling, heat treating (tempering), pickling, galvanizing, coating, or painting. Many of these steps require additional heating or reheating. The additional heating or reheating is accomplished using furnaces usually fired with natural gas. The furnaces are custom designed for the type of steel, the dimensions of the semi-finished steel pieces, and the desired temperature.

There are many different types of combustion processes at both Integrated Iron and Steel and EAF steel facilities that are not directly related to the major production processes previously discussed. The EAF facilities burn natural gas almost exclusively in their combustion units, whereas Integrated Iron and Steel facilities burn a combination of fuels, including natural gas, COG, and BFG in their combustion units. The combustion units at both types of facilities include boilers, process heaters, flares, dryout heaters, and several types of furnaces. For example, soaking pits and reheat furnaces are used to raise the temperature of the steel until it is sufficiently hot to be plastic enough for economical reduction by rolling or forging. Annealing furnaces are used to heat the steel to relieve stresses formed through mechanical strain (hot or cold working) as well as stresses induced by rapid cooling (quenching). Annealing also softens the steel to improve machineability and formability. Ladle reheating uses natural gas to keep the ladle hot while waiting for molten steel.

V. Energy Programs and Management Systems

Industrial energy efficiency can be enhanced by informed management of the energy use by operations and processes. There are formal energy management programs available, both with and without additional cost, as well as facility- or industry-specific programs. Because energy is a major part of a manufacturer's cost of production, many companies typically have strong internal programs that perform the same functions that the formal programs promote.

A. Formal Energy Programs

The EPA's ENERGY STAR Program (www.energystar.gov/industry) works with hundreds of U.S. manufacturers and has documented that companies and sites with stronger energy management programs gain greater improvements in energy efficiency than those that lack procedures and management practices focused on continuous improvement of energy performance. The EPA's ENERGY STAR Program and the U.S. Department of Energy's (DOE) Industrial Technology Program (www.energy.gov/energyefficiency) also have sponsored industry-specific energy efficiency initiatives over the years. These programs have helped to create guidebooks of energy efficient technologies, profiles of industry energy use, and studies of future technologies. Some states have also led sector-specific energy efficiency initiatives. Resources from these programs can help to identify technologies that may help reduce CO_2 emissions.

Energy Management Systems (EMS) provide a framework to manage energy and promote continuous improvement. The EMS provide the structure for an energy program. The EMS establish assessment, planning, and evaluation procedures that are critical for actually realizing and sustaining the potential energy efficiency gains of new technologies or operational changes.

The EMS promote continuous improvement of energy efficiency through:

- Organizational practices and policies;
- Team development;
- Planning and evaluation;
- Tracking and measurement;
- Communication and employee engagement; and
- Evaluation and corrective measures.

For nearly 10 years, the EPA's ENERGY STAR Program has promoted an EMS approach. This approach, outlined in the graphic below, shows the basic steps followed by most EMS approaches (www.energystar.gov/guidelines). In recent years, interest in the EMS approach has been growing. There are many reasons for the greater interest recently, which include recognition that a lack of management commitment is an important barrier to increasing energy efficiency. Further, lack of an effective energy team and energy efficiency program results in low implementation rates for new technologies or recommendations from energy assessments. Poor energy management practices that fail to monitor performance do not ensure that new technologies and operating procedures will achieve their potential in improving efficiency.

ENERGY STAR Guidelines for Energy Management

Approaches to implementing EMS vary. EPA's ENERGY STAR Guidelines for Energy Management are available for public use on the web and provide extensive guidance (see: www.energystar.gov/guidelines). Alternatively, Energy Management Standards (EM Standards) are available for purchase from American

National Standards Institute (ANSI) as ANSI's Management System for Energy (ANSI MSE 2001:200),[1] and in the future from International Standards Organization (ISO), as ISO 50001.[2]

While EMS can help organizations achieve greater savings through a focus on continuous improvement, they do not guarantee energy savings or carbon dioxide reductions alone. Combined with effective plant energy benchmarking and appropriate plant improvements, EMS can help achieve greater savings.

There is a variety of factors to consider when contemplating requiring certification to an EM Standard established by a standards body such as ANSI or ISO. First, EMS standards are designed to be flexible. A user of the standard is able to define the scope and boundaries of the EMS so that single production lines, single processes, an entire plant or corporation could be certified. Achieving certification for the first time is not based on efficiency or savings (although re-certifications at a later time could be). Finally, cost is an important factor in the standardized approach. Internal personnel time commitments, external auditor and registry costs are high. From a historical perspective, few companies have pursued certification according to the ANSI EM Standards to date. One reason for this is that the elements of an EMS can be applied without having to achieve certification, which adds additional costs. The ENERGY STAR Guidelines and associated resources are widely used and adopted partly because they are available in the public domain and do not involve certification.

Overall, a systems approach to energy management is an effective strategy for encouraging energy efficiency throughout a facility or corporation. The focus of energy management efforts are shifted from a "projects" to a "program" approach. There are multiple pathways available for the creation of EMS with a wide range of associated costs (ENERGY STAR energy management resources are publically available and free of cost, while ANSI or ISO standardized approaches are costly). The effectiveness of EMS are linked directly to the systems' scope, goals, and monitoring and recordkeeping. Benchmarks are the most effective measure for demonstrating the system's achievements.

Another resource for policy-makers is the Center for Clean Air Policy (CCAP) and CCAP's publications that provide an international perspective on climate policy. The CCAP is performing research and providing policy support to help policy-makers around the world develop, promote, and implement innovative, market-based solutions to major climate, air quality, and energy problems that balance both environmental and economic interests. The mission statement of the CCAP is to significantly advance cost-effective and pragmatic air quality and climate policy through analysis, dialogue, and education to reach a broad range of policy-makers and stakeholders worldwide. (For more information, see http://www.ccap.org/). In a study of global sectoral approaches (CCAP, 2010), CCAP investigated a trans-national approach in which all countries face similar benchmarks, a sectoral Clean Development Mechanism approach emphasizing carbon credits, and a bottom-up approach envisaging financial and technology assistance from advanced economies to support ambitious no-lose crediting baselines in developing countries. This study was supported by the Competitiveness and Innovation Framework Programme of the European Commission, and the study's objective was to help move beyond voluntary actions and facilitate participation by developing countries in international climate change actions.

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[1] ANSI MSE 2001:200 can be found at http://www.mse2000.net/.

[2] Available from the ANSI webstore at http://webstore.ansi.org/

B. Energy Performance Benchmarks on Plant- and Industry-specific Basis

Energy benchmarking is the process of comparing the energy performance of one site against itself over time or against the range of performance of the industry. Plant energy benchmarking is typically done at a whole-facility or site level in order to capture the synergies of different technologies, operating practices, and conditions. Benchmarking enables companies to set informed and competitive goals for plant energy improvement. Benchmarking also helps companies prioritize where to invest to improve poorly performing systems while learning from the approaches used by top performing systems.

When benchmarking is conducted across an industrial sector, a benchmark can be established that defines best in class energy performance. EPA's ENERGY STAR Program has developed benchmarking tools that establish "best-in-class" for specific industrial sectors. These tools, known as Plant Energy Performance Indicators, are established for specific industrial sectors and available for free at www.energystar.gov/industrybenchmarkingtools. Using several basic plant-specific inputs, the Plant Energy Performance Indicators calculate a plant's energy performance providing a score from zero to 100. The EPA defines the average plant within the industry nationally at the score of 50; energy-efficient plants score 75 or better. ENERGY STAR offers recognition for sites that score in the top quartile of energy efficiency for their sector using the Plant Energy Performance Indicators.

C. Industry Energy Efficiency Initiatives

Although a company may not formally participate in one of these Federal programs, it is not necessarily true that they are not actively engaged in improving energy efficiency. Many of the innovative approaches to energy efficiency have come from these internal industry programs where companies were able to be successful in reducing their total operating costs. As noted above, because energy is such a large part of the steel production costs, energy efficiency measures have been of interest to steel manufacturers for a long time. (AISI, 2011)

While cooperative efforts across the Iron and Steel industry sector to improve energy efficiency do exist, they can be met with some resistance because efficiency gains are business advantages that are part of the competitive and sometimes confidential business process. These advantages affect product pricing power and marketability. It is also possible that internal company driven efforts will bring equal or even greater returns than collective industry-wide efforts that may not address the unique nature of each company or facility in the steel industry. (AISI, 2011) Therefore, individual company energy efficiency projects may not be publically known and will need to be disclosed in confidence during the permitting process. However, many of the systems these companies use and from which they achieve cost savings are sold to all of the industry.

VI. Summary of GHG Control Measures

This section is a summary of the GHG control measures identified as potentially feasible for the Iron and Steel industry**.** All measures are energy efficiency measures**.** Reductions in fuel consumption result in reductions of direct emissions of GHGs at the steel plant, and reductions in electricity usage result in reductions of indirect GHG emissions (i.e., GHG emissions from the power plant supplying the electricity). **Table 1** summarizes the GHG control measures for Integrated Iron and Steel plants; **Table 2** summarizes the measures for EAF steelmaking. **Appendix C** includes additional information on these energy efficiency options and their costs taken from a study conducted for EPA and DOE and subsequently updated in another study for EPA's Climate Protection Partnerships Division as part of the ENERGY STAR Program. (Worrell, 2009) The tables in **Appendix C** include estimates of the emission reduction potential based on case studies available at the time of the report, and also include estimates of energy savings, costs, and feasibility of each measure where such information was available.

There are several important caveats associated with the information in the tables here and in **Appendix C** that require caution in extrapolating to every Iron and Steel plant. Because many of the measures were based on the experience of a single plant or an individual application of the measure, or in some cases best estimates based on the available information, the feasibility of the measure could be quite different when applying to other plants because of the numerous site-specific differences among plants that affect costs. In addition, many measures may not be applicable to certain plants because of the process configuration, product type or quality constraints, or the fact that the measure or a similar one has already been applied. Some equipment modifications may incur significant retrofit costs that affect the ability to implement the measure in a specific situation. The choice of which measures might be the most appropriate to implement at a given facility should be based on a detailed analysis that assesses site-specific costs, savings, and potential GHG emission reductions.

An industry trade association (AISI, 2011) provided comments on the technical feasibility and cost-effectiveness of each of the various energy options in **Tables 1** and **2**. The industry comments indicate one or more of the following conditions for the options presented: (1) site-specific variables may exist that affect costs and/or practicality of using the option at all facilities; (2) energy efficiency may be improved and potentially lower GHG emissions, but emissions of other pollutants may increase; (3) already widely implemented at most existing facilities; (4) only feasible for new units; (5) an immature technology and/or practice because it is still being researched and/or is in the pilot stage, at least as applied to Iron and Steel; and (6) a specialized process only technically appropriate for some equipment configurations or types. A general note made by industry representatives is that payback times of more than three years are not likely to be considered economically feasible by a facility. (AISI, 2011)

VII. Energy Efficiency Improvement Measures for the Steel Industry

This section describes the energy efficiency measures that may be feasible for GHG control in the Iron and Steel industry. All measures reduce fuel consumption and, therefore, produce direct and indirect reductions in fuel-associated GHG emissions. The Iron and Steel industry is an energy intensive industry. However, industry-wide technology advances, such as new process adoption and widespread adoption of advanced process controls, have reduced energy intensity by 30 percent since 1990. (AISI, 2011) See **Appendix B** for the data. While many of the options described in this document available to reduce GHG emissions involve improved energy efficiency, future reductions industry-wide along the lines achieved since 1990 may require development and commercialization of a large number of breakthrough technologies. (AISI, 2011) See **Appendix A** for a description of these technologies.

The following descriptions of potential energy mitigation options correspond to those in **Tables 1** and **2** and were taken primarily from data obtained from the study by Worrell (1999, 2009) discussed in **Appendix C** and shown in **Tables C-1** and **C-2**. In many cases, the descriptions below were taken verbatim from the two research reports (unless indicated otherwise). Specific references are given when new or additional material was obtained from other sources. Costs and payback times are presented when available. All costs are presented in 2008 dollars. All references to "per ton" or to "per tonne" refer to tons or tonnes of product from the process that is being discussed.

The relative costs shown here do not reflect changes in actual conditions, such as the installation of new and possibly better equipment, which may have reduced the need for additional energy-saving technology while producing similar reductions in GHG emissions. Although the options in the tables are good examples of the types of operational changes possible to reduce energy consumption, site-specific details of the operations can vary significantly from plant to plant so that in some cases the estimated cost savings may not be realized. Consequently, any implementation of the technologies cited here may not actually achieve in reality as high a reduction in GHG emissions as cited in the case studies. (AISI, 2011)

Table 1. Energy Efficiency Technologies and Measures Available for Integrated Steel and Coke Production in the U.S.[a] (Worrell, 1999, 2009; AISI, 2011)

Option	Applicability and Feasibility Codes (see list of codes below)[b]	Payback Time (years)[c]
Iron Ore Preparation (Sintering)		
Sinter plant heat recovery	C	2.8
Emission optimized sintering		
Reduction of air leakage	C	1.3
Increasing bed depth	C, S	0.0
Improved process control	C, EX	1.4
Use of waste fuels (e.g., lubricants) in sintering	C, S	0.5
Improve charging method		
Improve ignition oven efficiency		
Cokemaking		
Coal moisture control	C, EX	> 50
Programmed heating	C, EX	0.7
Variable speed drive COG compressor	C	21.2
Coke dry quenching	C	35.7
Additional use of COG	C, EX	
Single chamber system	C, N	
Non-recovery coke ovens	C, EX	
Ironmaking - Blast Furnace		
Pulverized coal injection to 130 kg/ton iron		2.0
Pulverized coal injection to 225 kg/ton iron	C, N	2.4
Injection of natural gas to 140 kg/ton iron	C, EX	1.3
Injection of oil	C	
Injection of COG and BOF gas	C	<1.0
Charging carbon composite agglomerates	P	
Top pressure recovery turbines (wet type)	C, N	29.8
Recovery of BFG	C, EX	2.3
Hot-blast stove automation	EX	0.4
Recuperator hot-blast stove	C	8.7
Improvement of combustion in hot stove	C, EX	
Improved blast furnace control systems	EX	0.4
Blast furnace gas recycling	P	
Slag heat recovery	P	
Steelmaking - Basic Oxygen Furnace (BOF)		
BOF gas plus sensible heat recovery	C	11.9
Variable speed drive on ventilation fans	C, EX	9.9
Improvement of process monitoring/control	EX	
Programmed and efficient ladle heating	C, EX	
Casting		
Efficient caster ladle/tundish heating	C, EX	1.3
Near net shape casting - thin slab	N, S	3.3
Near net shape casting - strip	N, S	

Option	Applicability and Feasibility Codes (see list of codes below)[b]	Payback Time (years)[c]
General Measures for Rolling Mills		
Energy efficient drives	EX	3.2
Gate communicated turn-off inverters		
Install lubrication system	EX	
Hot Rolling		
Proper reheating temperature		
Avoiding overload of reheat furnaces	EX	
Hot charging	EX, N, S	5.9
Process control in hot strip mill	EX	1.2
Recuperative and regenerative burners	C, EX	1.8
Flameless burners	C	
Insulation of furnaces	C, EX	31.0
Walking beam furnace	C, EX, N	
Controlling oxygen levels and/or speed on combustion air fans	C	0.8
Heat recovery to the product	C. N	
Waste heat recovery (cooling water)	C, P	> 50
Cold Rolling and Finishing		
Heat recovery on the annealing line	C, EX	4.0
Reduced steam use (pickling line)	C, EX	7.3
Automated monitoring and targeting system	C, EX	0.8
Inter-electrode insulation in electrolytic pickling line	P	
Continuous annealing	N	
General		
Preventive maintenance	EX	
Energy monitoring and management system	EX	0.5
Combined heat and power/cogeneration	EE, EX, N	6.1
High-efficiency motors		
Variable speed drives: flue gas control, pumps, and fans	C, EX	10.7

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[a] See **Appendix C** for estimates of energy savings and costs for these process changes and measures prepared by Worrell (1999, 2009).

[b] Applicability codes (AISI, 2011):

C	=	Site-specific variables may affect costs and/or practicality of use of the option at all facilities.
EE	=	Options that could improve energy efficiency and potentially lower GHG emissions but may increase other pollutants.
EX	=	Process already widely implemented at many existing facilities.
N	=	Only feasible for new units.
P	=	Immature process that is still in research and/or pilot stage as applied to Iron and Steel.
S	=	Specialized process only technically appropriate for some equipment configurations or types.

[c] Options with payback times of more than three years are not likely to be considered economically feasible by a facility. (AISI, 2011)

Table 2. Energy Efficiency Technologies and Measures Available for Electric Arc Furnace Steel Production in the U.S.[a] (Worrell 1999, 2009; AISI, 2011)

Option	Applicability and Feasibility Codes (see list of codes below)[b]	Payback Time (years)[c]
Steelmaking - Electric Arc Furnace		
Improved process control (neural network)	EX	0.5
Adjustable speed drives	EX	2–3
Transformer efficiency—ultra-high power transformers	C, EX	5.2
Bottom stirring/stirring gas injection	C, EE, N	0.2
Foamy slag practice	C, EX	4.2
Oxy-fuel burners	C, EX	0.9
Post-combustion of the flue gases	C, EX,	
DC arc furnace	C, N	
Scrap preheating—tunnel furnace (Consteel)	C, EE, S	
Scrap preheating, post-combustion—shaft furnace (Fuchs)	C, EE, N, S	
Engineered refractories		
Airtight operation	P	
Contiarc furnace	C, N, S	
Flue gas monitoring and control	C, EX	4.3
Eccentric bottom tapping on existing furnace	C, N, S	6.8
DC twin-shell with scrap preheating	C, EE, N	3.5
Casting		
Efficient caster ladle/tundish heating	EX	1.3
Near net shape casting - thin slab	C, EX	3.3
Near net shape casting - strip	C	
Hot Rolling		
Proper reheating temperature	EX	
Avoiding overload of reheat furnaces	EX	
Energy efficient drives in the rolling mill	EX	5.9
Process control in hot strip mill	EX	1.2
Recuperative and regenerative burners	C, EX	1.8
Flameless burners	C, EX	
Insulation of furnaces	C, EX	31.0
Walking beam furnace	C, N	
Controlling oxygen levels and/or variable speed drives on combustion air fans	C, P	
Heat recovery to the product	C	
Waste heat recovery (cooling water)	C, P	> 50
General		
Preventive maintenance	EX	
Energy monitoring and management systems	EX	0.9

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[a] See **Appendix C** for estimates of energy savings and costs for these process changes and measures prepared by Worrell (1999, 2009). See Table 1 for energy efficiency measures applicable to rolling and finishing operations.

[b] Applicability codes (AISI, 2011):

C = Site-specific variables may affect costs and/or practicality of use of the option at all facilities.
EE = Options that could improve energy efficiency and potentially lower GHG emissions but may increase other pollutants.
EX = Process already widely implemented at many existing facilities.
N = Only feasible for new units.
P = Immature process that is still in research and/or pilot stage as applied to Iron and Steel.
S = Specialized process only technically appropriate for some equipment configurations or types.

[c] Options with payback times of more than three years are not likely to be considered economically feasible by a facility. (AISI, 2011).

A. Sintering at Integrated Iron and Steel Plants

The following are descriptions of potential energy mitigation options for sintering operations at Integrated Iron and Steel plants.

Sinter Plant Heat Recovery

Heat recovered from the sinter plant can be used to preheat the combustion air for the burners and to produce high-pressure steam, which can then be used in steam turbines to generate power. Various systems exist for new plants (e.g., Lurgi emission optimized sintering process), and existing plants can be retrofitted. Based on a retrofitted facility in The Netherlands, fuel savings were estimated to be 0.47 MMBtu/ton (0.55 GJ/tonne) of sinter, and increased electricity generation was estimated to be 1.4 kilowatt hour per ton (kWh/ton) (0.0056 GJ/tonne) of sinter. The payback time was estimated as 2.8 years. Emissions of nitrogen oxide (NO_x), sulfur oxide (SO_x), and PM are expected to be reduced. Capital costs are approximately $4.28 ton ($4.72/tonne) of sinter. Steam generation with sinter cooler gases using a waste heat boiler is common in Japan and was reported to recover 0.22 MMBtu/ton sinter (0.25 GJ/tonne).

Emission Optimized Sintering

This process for sinter plants was developed by Outokumpu Technology in the 1990s and can be retrofitted with minimal production interference. It reduces the substantial off-gas volume by 50 to 60 percent through housing the entire sinter strand, re-circulating off-gases, and using its CO content as an energy source to minimize off-gas volumes. The process reduces off-gas cleaning investment costs, saves energy in the form of coke, reduces operational costs, and significantly reduces NO_x, SO_x, CO, and CO_2 emissions.

Reduction of Air Leakage

Reducing air leakage from the sintering plant reduces fan power consumption by approximately 2.7 to 3.6 kWh/ton (0.011 to 0.014 GJ/tonne) of sinter. Costs of repairs to fix the leaks were estimated to be $0.13/ton ($0.14/tonne) of sinter capacity. Payback time was estimated as 1.3 years. (Improving fan efficiency is a potential energy saving option in other Iron and Steel sector processes as well as in other industrial sectors.)

Increasing Bed Depth

Increasing the bed depth in the sinter plant can lower fuel consumption, improve product quality, and increase productivity slightly. Fuel consumption may decrease by 0.6 pounds (lb) of coke/ton of sinter per 0.4 inch (in) bed thickness increase (0.3 kilogram [kg] of coke/tonne of sinter per 10 millimeters [mm] bed thickness increase). Electricity savings may be 0.05 kWh/ton (0.002 GJ/tonne) of sinter.

Improved Process Control

Based on general experience with industrial control and management systems, improved process controls may result in savings of 2 to 5 percent of energy use. Assuming a 2 percent savings, this would equate to a primary energy savings of approximately 0.04 MMBtu/ton (0.05 GJ/tonne) of sinter. Capital costs were estimated to be $0.19/ton ($0.21/tonne) of sinter. The payback time was estimated as 1.4 years.

Use of Waste Fuels in Sinter Plant

Waste materials with available caloric content (e.g., oils from the cold rolling mill) can be used as fuel and reduce the energy demand satisfied by the primary fuel. Estimates of the energy savings for this measure are difficult to make without knowing the quality and quantity of the waste material. Use of the waste material may be limited by permitted emissions limits because oils and other organics in the sinter feed increase emissions of organic compounds (including benzene, other volatile organic compounds dioxins, etc.). Based on data from European mills, the energy savings may amount to 0.15 MMBtu/ton (0.18 GJ/tonne) of sinter. The savings for this measure depend on the composition and quantity of lubricants and the installed gas clean-up system at the sinter plant. In addition, the emission control systems are unlikely to be able to control well the organic products of incomplete combustion that accompany these efforts to reduce energy consumption. One plant, however, reportedly developed a waste recovery and waste injection system at a cost of about $25 million to recycle 200,000 tons (180,000 tonnes) per year of various materials. Capital costs were estimated to be $0.26/ton ($0.29/tonne) of sinter. The payback time was estimated at 0.5 years.

Improve Charging Method

Ore used as a raw material for sintering is inexpensive, but it decreases the productivity in the sintering process because it combines strongly with water and has a coarse particle size. These problems can be overcome by using an improved charging method. The system adopts a drum chute and a segregation slit wire. The purpose of the drum chute is to reduce the height difference (dropping difference) in material charging, while the segregation slit wire controls the particle size distribution. Specifically, because a constant particle size is maintained, the permeability of the sintering mixture is increased, resulting in improved sintering efficiency, and the material return ratio due to poor sintering is reduced. This system was developed by a Japanese steelmaker and has been introduced at all its plants in Japan. Productivity improvement amounts to 5 percent and energy consumption due to coke use decreases by 0.07 MMBtu/ton sinter (0.08 GJ/tonne sinter) compared to a conventional charging system.

Improve Ignition Oven Efficiency

A large fuel reduction can be achieved by improving the ignition oven efficiency. To reduce the fuel needed for ignition ovens, a heat retention oven was removed from a large capacity conventional ignition oven, and a smaller capacity ignition oven was substituted. The inner pressure of the smaller ignition oven was regulated by controlling individual windbox cells located immediately underneath the ignition oven.

A burner that can achieve rapid heating and uniform ignition in the pallet width direction has been developed and introduced to realize large fuel reductions. This burner consists of fuel exhaust nozzles located in the sintering floor width direction and a slit-like burner tile containing these fuel exhaust nozzles. The fuel supplied from the fuel exhaust nozzles reacts with the primary air inside the burner tile, then to the secondary air supplied to flame the outer periphery area. By using the slit-like burner tile, non-flamed places could be eliminated, and by controlling the ratio between the primary air and the secondary air, the length of the flame could be controlled to minimize the ignition energy. In this case, the ignition energy was reduced by approximately 30 percent.

Other Measures

Other measures include the use of higher quality iron ores, low iron oxide (FeO) content, replacing silicon dioxide (SiO_2) with magnesium oxide (MgO), reduction of the basicity of the sinter to the proper range (1.5 to 2.0), and the use of coarse coke breeze.

B. Cokemaking

The following are descriptions of potential energy mitigation options for coke making operations.

Coal Moisture Control

Waste heat from the COG can be used to dry the coal used for cokemaking, which may reduce the fuel consumption in the coke oven by approximately 0.26 MMBtu/ton (0.3 GJ/tonne). The cost of equipment to control coal moisture for a plant in Japan was $69.5/ton ($76.6/tonne) of steel. Application of the technique leads to a reduction of 0.11 to 0.18 MMBtu/ton coal (0.13 to 0.21 GJ/tonne) in carbonization heat requirements, while the strength of the coke[3] is improved by approximately 1.7 percent and productivity by about 10 percent. The payback time was estimated at over 50 years.

Programmed Heating

The use of programmed heating instead of conventional constant heating of the coke ovens can help ensure optimization of the fuel gas supply to the ovens during the coking process. This measure can result in fuel savings of 10 percent, or approximately 0.15 MMBtu/ton (0.17 GJ/tonne) of coke. Capital costs for the computer control system were estimated to be $113,250/coke battery, or approximately $ 0.33/ton ($0.37/tonne) of coke capacity. The payback time was estimated as 0.7 years.

Variable-Speed Drive COG Compressors

Although COG is generated at low pressures and then pressurized for transport in the internal gas grid, the COG flows vary over time due to the coking reactions. The use of variable-speed–drive (VSD) COG compressors can reduce the energy required for compression of the low-pressure gas for transport. The VSDs help to compensate for variability in the gas flow due to coking reactions. One facility in The Netherlands installed a VSD system at

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[3] The physical strength of the coke is a critical parameter when the coke is charged to the blast furnace to prevent damage to the furnace if the charge materials (called the "burden") were to collapse and block the passageway for the gases and blast air that move through the charge materials.

a cost of \$0.43/ton (\$0.47/tonne) of coke and realized energy savings of 0.005 to 0.007 MMBtu/ton (0.006 to 0.008 GJ/tonne) of coke. The payback time was estimated as 21 years.

Coke Dry Quenching

Dry quenching of the coke, in place of wet quenching, can be used to recover sensible heat that would otherwise be lost from the coke while reducing dust. The steam recovery rate with this equipment is about 0.5 MMBtu/ton (0.55 GJ/tonne) coke. In addition, Nippon Steel's performance record shows that the use of coke manufactured by dry quenching reduces the amount of coke consumption in the blast furnace by 0.24 MMBtu/ton (0.28 GJ/tonne)[4] molten iron. The payback time was estimated as 36 years. For new plants, the cost of the dry-quenching system was estimated to be \$99.3/ton (\$109.5/tonne) of coke. Retrofit costs depend strongly on the facility layout and can run as high as \$118 to 152/MMBtu (\$112 to 144/GJ) saved. Coke dry quenching has not been applied to any Coke plants in the U.S.

Additional Use of Coke Oven Gas

Although COG is a low-Btu gas, approximately 40 percent of the COG is used as a fuel in coke ovens in the U.S. In most U.S. steel plants, the remaining COG is used to fuel equipment such as reheat furnaces and boilers that supply steam for electricity generation, turbine driven equipment such as pumps and fans, and for process heat. To the extent that any of the COG is flared at a facility, it could instead be used in combustion processes to offset the consumption of natural gas.

Single Chamber System

Single chamber system coking reactors (formerly called Jumbo Coke Reactors) are coke ovens with large coke oven volume and widths, between 17.7 to 33.5 in (450 to 850 mm). The process includes the use of preheated coal. The reactors are separate process controlled modules with rigid, pressure stable, heating walls to absorb high coking pressure. This allows much thinner heating walls to be constructed, thus improving heat transfer and combustion, and greatly increasing the design flexibility of the plant. The high load bearing capacity of the side walls allows a greater range of coal bends to be charged, and the larger dimension ovens decrease the emissions of pollutants into the environment. The coal preheater increases coal bulk density, reduces the coking time, improves productivity and leads to increased coke strength. It is expected that these coke ovens are able to take the place of current multi-chamber batteries with walls of limited flexibility. Single chamber system coking reactors have an improvement in thermal efficiency from 38 percent to 70 percent, but the technology is currently under development.

Non-recovery Coke Ovens

In the non-recovery coking process, raw COG and other by-products released from the coking process are combusted within the oven, offering the potential for heat recovery and cogeneration of electricity. As the ovens operate under reduced pressure and at a temperature at which all potential pollutants break down into combustible compounds, this technique consumes all by-products, eliminating much of the potential for air emissions during the coking process and water pollution associated with the conventional byproduct recovery process. The process thus requires a different oven design from that traditionally used, resulting in a larger required area. A COG treatment plant and wastewater treatment plant are not needed.

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[4] Using net calorific value of 28,299 GJ/Gg coking coal.

When the waste gas exits into a waste heat recovery boiler, which converts excess heat into steam for power generation, the process is called heat recovery cokemaking. The four newest Coke plants built in the U.S. have been the heat recovery type. In Haverhill, Ohio, a plant produces 500,000 tons (450,000 tonnes) of coke per year while producing 220 tons/hr (200 tonne/hr) of steam, some of which is used in a nearby chemical plant and some used to generate electricity. Another plant in Granite City, Illinois, produces 650,000 tons (590,000 tonnes) of blast furnace coke per year and approximately 250 ton/hr (225 tonne/hr) of superheated steam.

C. Blast Furnace at Integrated Iron and Steel Plants

The following are descriptions of potential energy mitigation options for blast furnaces at Integrated Iron and Steel plants.

Pulverized Coal Injection

Almost all Integrated Iron and Steel plants have implemented pulverized coal injection at varying injection rates. Pulverized coal and natural gas injection replaces the use of coke, thereby reducing coke production and saving the large amount of energy consumed in cokemaking, reducing emissions from coke ovens, and reducing maintenance costs. However, increasing fuel injection requires energy for the oxygen and coal injection, electricity, and equipment to grind the coal. Some amount of coke is still used as support material in the blast furnace. In one application, the average coal injection rate into the blast furnace increased from approximately 4 lb/ton (2 kg/tonne) of hot metal to approximately 260 lb/ton (130 kg/tonne) of hot metal. The energy savings in the blast furnace due to coal injection have been calculated at 3.23 MMBtu/ton (3.76 GJ/tonne) coal injected. Fuel savings were estimated to be 0.66 MMBtu/ton (0.77 GJ/tonne) of hot metal, with capital costs of $9.92/ton ($10.94/tonne) of hot metal. Operating costs may decrease by $2.83/ton ($3.12/tonne) of hot metal. Investment costs for coal grinding equipment were estimated to be $45 to 50/ton ($50 to 55/tonne) of coal injected. The payback time is estimated as 2.0 to 2.4 years.

There is a practical upper limit to the scale of pulverized coal injection that can be used. The limit on PCI rates will depend on coal types and raw material qualities among other variables. Coal injection rates above 400 lb/ton (200 kg/tonne) of hot metal are considered massive and may not be sustained for long periods of time especially for large furnaces. (AISI, 2011)

Natural Gas Injection

Natural gas injection is typically applicable only to medium-sized furnaces having production rates of 1.4 to 2.5 million tons per year (tpy) (1.3 to 2.3 million tonnes/yr). Natural gas injection is an alternative to coal injection, and its selection depends on the price of natural gas versus coal. Replacement rates for natural gas may range from approximately 0.9 to 1.15 ton natural gas/ton coke (0.9 to 1.15 tonne of natural gas/tonne of coke). Estimated capital costs are $7.1/ton ($7.82/tonne) of hot metal. Estimated cost savings range from $3.6 to 4.5/ton ($4 to 5/tonne) of hot metal, and energy savings for a typical process were estimated to be 0.8 MMBtu/ton (0.9 GJ/tonne) of hot metal. Natural gas can be injected simultaneously with pulverized coal. It was reported that the rate by which natural gas injection can compensate for coal injection was a value of 6,400 to 16,000 ft^3/ton (200 to 500 m^3/tonne), depending on fuel composition and technological conditions. The payback time is estimated as 1.3 years.

Oil Injection

Heavy fuel oil or waste oil can also be injected instead of coke. The coke replacement rate is 1 ton of oil (0.9 tonnes) to replace 1.2 tons (1.1 tonnes) of coke. Like natural gas, oil contains hydrogen, leading to decreased CO_2 emissions. If oil injection is used along with oxygen burner technology, the amount of oil injected can be increased by 100 percent as compared to regular burners. This increase would correspond to a one-to-one weight ratio between the oil injected and the hot metal produced.

Injection of COG and BOF Gas

Coke oven gas and BOF gas can also be injected into blast furnace to reduce CO_2 emissions, since these gases contain less carbon than coke. The maximum level for COG injection at the tuyère level is thought to be 0.1 ton COG/ton hot metal (0.1 tonne COG/tonne hot metal). The equivalent replacement rate of coke is about 1 ton of COG for 0.98 ton of coke (0.9 tonne of COG for 0.89 tonne of coke). This limit is set by the thermochemical conditions in the furnace. Coke oven gas injection is successfully being employed in both blast furnaces at the U. S. Steel plant in Braddock, PA. (AISI, 2011)

Charging Carbon Composite Agglomerates

Carbon composite agglomerates are mixtures of fine iron ore (hematite, magnetite, iron-bearing dust and pre-reduced iron-bearing ore fines) and fine carbonaceous materials (fine coke, fine coal, charcoal, and char) with some binding agents added to the mixture in most cases. These agglomerates were tested in operating blast furnaces and blast furnace simulators and were found to improve the energy efficiency of a blast furnace. Furthermore, the effective use of non-coking coal, and iron-bearing dust and sludge in steel works would reduce the amount of raw materials needed and promote resource recycling.

Top Pressure Recovery Turbines (Wet Type)

Top pressure recovery turbines are used to recover the pressure in the furnace. Although the differential pressure between the furnace and atmosphere is low, the large volume of gas may make recovery of the furnace pressure economical. The turbine may produce approximately 14 to 36 kWh/ton (0.054 to 0.14 GJ/tonne) of hot metal. Although the top pressure in most U.S. furnaces is too low for recovery, future upgrades to furnaces may result in pressures high enough to allow economical recovery. (Upgrades occur every few years when the furnace is shutdown and re-lined. During these events, there is an opportunity to upgrade other equipment associated with the furnace operation.) Typical investment for the turbine is approximately $28.4/ton ($31.3/tonne) of hot metal. The payback time is estimated as 30 years.

Recovery of Blast Furnace Gas

Approximately 1.5 percent of the gas used in the blast furnace may be lost during charging, which could be recovered. A recovery system has been installed on a furnace in The Netherlands at a cost of $0.43/ton ($0.47/tonne) of hot metal. Energy savings have been estimated to be approximately 17 kWh/ton (0.066 GJ/tonne) of hot metal. The payback time is estimated as 2.3 years.

Hot-blast Stove Automation

This measure can reduce energy consumption of the stoves by running the operation more efficiently and closer to optimum conditions. Energy savings typically range between 5 and 12 percent, and may reach 17 percent.

Typically, this may equate to 93 kWh/ton (0.037 GJ/tonne) of hot metal. The installation of a control system on a furnace in Belgium had a payback period of 2 months. Investment costs were assumed to be approximately \$0.43/ton (\$0.47/tonne) of hot metal. The payback time is estimated as 0.4 years. At the former ISPAT Island plant, the application of a model based controller for the optimal operation of blast stoves has led to 6 to 7 percent reductions in natural gas use and an improvement of operational consistency.

Recuperator Hot-Blast Stove

The hot-blast stove flue gases can be used to preheat the combustion air of the blast furnace. Various systems have been implemented, with fuel savings ranging from 20 to 21 kWh/ton (0.080 to 0.085 GJ/tonne) of hot metal at a cost of approximately \$19 to 21/MMBtu (\$18 to \$20/GJ) saved (equivalent to approximately \$2.0/ton [\$2.2/tonne] of hot metal). Preheating can lead to an energy saving of approximately 0.3 MMBtu/ton pig iron (0.35 GJ/tonne). An efficient hot-blast stove can run without the need for natural gas. For a specific medium-type waste heat recovery device (consisting of two heat exchangers), a recovery rate of sensible heat of 40 to 50 percent and a reduction in heat consumption of about 0.108 MMBtu/ton pig iron (0.126 GJ/tonne) produced has been reported. The payback time is estimated as 8.7 years.

Improvement of Combustion in Hot Stove

Improvement of combustion through more efficient burners and adaptation of combustion conditions (fuel/oxygen ratio) are estimated to lead to savings of 0.03 MMBtu/ton (0.04 GJ/tonne) pig iron.

Improved Blast Furnace Control Systems

Control systems have been developed in the U. S., Europe, and Japan to improve the control of the blast furnace. Estimated energy savings were approximately 0.34 MMBtu/ton (0.4 GJ/tonne) of hot metal. Capital costs were estimated to be approximately \$0.5 million per blast furnace, or approximately \$0.51/ton (\$0.56/tonne) of hot metal. The implementation of a closed-loop blast furnace automation system at Voest Alpine (Linz, Austria) has resulted in a reduced coke consumption of approximately 0.46 ton/ton of hot metal (0.46 tonne/tonne of hot metal) in 2000, as well as reduced steam consumption by approximately 10.5 ton/hr (9.5 tonne/hr). The payback time is estimated as 0.4 years.

Blast Furnace Gas Recycling

Recirculation of the reducing gas components (CO and H_2) of the blast furnace gas formed in the furnace has been considered as an effective method to improve the blast furnace performance, enhance the utilization of carbon and hydrogen, and reduce the emission of carbon oxides. Previously, various recycling processes have been suggested, evaluated, or practically applied for different objectives. These processes are distinguished from each other by: (1) use with or without CO_2 removal, (2) use with or without preheating, and (3) position of injection. This technology has not been commercially developed or deployed but it is the focus of intensive R&D in the Ultra-Low CO_2 Steelmaking (ULCOS) program.

Slag Heat Recovery

In modern blast furnaces, around 0.25 to 0.30 ton (0.23 to 0.27 tonne) liquid slag with a temperature of approximately 2,640 degrees Fahrenheit (°F) (1,450 degrees Celsius [°C]) is produced per ton pig iron. None of the current slag heat recovery systems have been applied commercially. This is due to the technical difficulties that would arise in the development of a safe, reliable, and energy efficient system that does not influence the slag quality.[5] One difficulty is that heat recovery from slag only becomes practical when the slag is granulated.[6] If such a technique were to be developed, associated estimated savings would be approximately 0.30 MMBtu/ton (0.35 GJ/tonne) pig iron.

D. Basic Oxygen Furnace at Integrated Iron and Steel Plants

The following are descriptions of potential energy mitigation options for BOF at Integrated Iron and Steel plants.

BOF Heat and Fuel Gas Recovery

The BOF in the U.S. are either open-hood or closed-hood vessels (approximately 50 percent of each type). When oxygen is blown into the BOF to remove carbon to make steel, most of the carbon is removed as CO. In the open-hood BOF, large quantities of outside air are drawn into the BOF exhaust hood to burn the CO, and the exhaust gas reaches temperatures of 3,500ºF (1,900°C). The exhaust gas from the open-hood BOF has no fuel value; however, both types of BOF offer opportunities for heat recovery because of the high temperatures of the exhaust gas. Closed-hood BOF suppress or prevent the intake of air, and the resulting exhaust gas at 3,000ºF (1,650°C) is much lower in volume than from an open hood. In addition, the closed-hood BOF generates an exhaust gas with fuel value from the CO. Newer BOF are the closed-hood design, which has lower operating costs; however, no new BOF have been installed in the U.S. in more than 30 years.

The closed-hood BOF offer the best opportunity for both heat and fuel recovery. Although heat and fuel gas recovery from BOF is very common in Japan and Western Europe, it has not been implemented in the U.S. This is likely due to the economics of retrofitting old BOF shops. However, BOF gas and heat recovery is one of the most beneficial energy-saving process improvements for steelmaking. In steel plants in other countries, which use BOF gas, the predominant use is in the boiler plant, either directly or blended with BFG. BOF gas and BFG have also been used in gas turbine–combined cycle units, which are much more efficient in producing power than a conventional boiler and steam turbine generator set.

The energy recovery would reduce CO_2 generation from the use of natural gas and electricity by approximately 0.05 ton of CO_2/ton of steel (0.05 tonne of CO_2/tonne of steel), which would offset a significant portion of the unavoidable generation of CO_2 from steelmaking (estimated at 0.11 to 0.16 ton of CO_2/ton of steel) (0.11 to 0.16 tonne of CO_2/tonne of steel). Energy savings range from 0.46 to 0.79 MMBtu/ton (0.53 to 0.92 GJ/tonne). The capital cost of the recovery system is estimated at roughly $22/ton ($20/tonne) of steel (or approximately $66 million for an average BOF shop with a production rate of 3 million tons per year (2.7 million tonnes per year). The payback period is estimated as 12 years.

Variable-Speed Drives on Ventilation Fans

The BOF process is a batch process, leading to widely varying volumes of flue gas. Thus, installing VSD can reduce energy consumption. At one facility, VSDs reduced energy consumption by 20 percent, or 0.82 kWh/ton (0.003 GJ/tonne) of crude steel. Investment costs are approximately $1.7 million, or approximately $0.28/ton ($0.31/tonne) of crude steel. At the Burns Harbor steelmaking facility, VSDs and equipment modifications

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[5] Slag quality is important because it is a useful and valuable by-product, and over the past 25 years, all blast furnace slag produced in the U.S. has been used. These uses include aggregate for road bases, asphalt concrete, and concrete; production of mineral wool, cement, and glass; structural fill; and railroad ballast.

[6] Granulated blast-furnace slag is produced by quickly quenching (chilling) molten slag to produce a glassy, granular product. The most common process is quenching with water, but air or a combination of air and water may be used.

reduced energy use at the BOF by about 50 percent and reduced operation and maintenance expenses. The payback time was under 2 years.

Improvement of Process Monitoring and Control

Various types of monitoring systems make it possible to increase process control, which can lead to increased productivity and energy and cost savings. Examples of such systems are exhaust gas analysis systems, a contour sensoring system, and simultaneous determination of steel/slag composition. The monitored data can also be used as input into models of the BOF process, which can help to improve understanding and to optimize the process. An example of process control system is an oxygen management system for oxygen supply to the BOF process. The total savings due to this system are estimated at 1.5 percent of the electricity used for oxygen production. The payback time is approximately 3 years (Worrell, 2010).

Programmed and Efficient Ladle Heating

The ladle of the BOF vessel is preheated with gas burners. Fuel consumption for preheating the ladle containing liquid steel is estimated at 0.017 MMBtu/ton (0.02 GJ/tonne) liquid steel. Heat losses can occur through the lack of lids and through radiation. The losses can be reduced by installing temperature controls, installing hoods, by efficient ladle management (reducing the need for preheating), using recuperative burners, and use of oxy-fuel burners.

Programmed ladle heating minimizes the quantity of fuel required to bring ladles up to steel handling temperatures. This may include the scheduling of ladle heating to ensure that ladles are not kept on heat for excessive periods as well as control of the combustion process. Furthermore, an efficient burner for ladle pre-heating makes sure that fuels are used efficiently.

JFE Steel Corporation's West Japan Works in Kurashiki improved the design of their ladle heating system by adopting a high-speed online heating apparatus and by developing a control system that combined this heating system with the control of the blowers in a BOF. In comparison with the heat balance before the introduction of the new process, the ratio of the amount of heat stored in a ladle refractory to the amount of heat input into a ladle improved by more than 10 times from 6.5 percent to 67.5 percent. The amount of heat stored in the ladle refractory at the time of receiving molten steel from the BOF became 6.3 times as large, which made it possible to reduce steel temperature at tapping by 16°F (9°C), thereby reducing the amount of carbon (coke) used to raise steel temperature in a converter by 16 percent.

E. Casting

The following are descriptions of potential energy mitigation options during casting operations that could be used at both Integrated Iron and Steel and EAF plants.

Efficient Ladle Preheating and Tundish Heating

The ladle of the caster is preheated with gas burners with a fuel consumption estimated at 0.02 MMBtu/ton (0.02 GJ/tonne) liquid steel. Heat losses can occur through lack of lids and through radiation. The losses can be reduced by installing temperature controls, installing hoods, by efficient ladle management (reducing the need for preheating), using recuperative burners, and using oxy-fuel burners.

Tundishes are heated to reduce the heat loss of the molten steel, to avoid bubbles in the first slab at the beginning of the casting sequence, and to avoid degeneration of the refractory due to thermal shocks. Combustion-heated tundishes on average are only 20 percent efficient. Although earlier tundishes heated through electrical induction failed to generate enough heat to be effective in the manufacturing process, new methods have been developed to improve heating capacity. Tundishes heated by electrical induction have the potential to reach efficiency levels of 98 percent; however, the use of electricity may result in indirect energy losses in power generation. Energy savings can also be attained by refraining from heating the tundish. Practices at a plant in Brazil have shown that the use of a cold tundish is operationally feasible and that it brings with it several main benefits: a 70 percent reduction in the time for machine return after interruptions at the beginning of the cycle, a 78 percent reduction of natural gas consumption, a 90 percent increase of the lifetime of the tundish lids, and improvement of the working conditions on the casting platform due to heat and noise reductions. (Percentages are expressed on a per process unit basis). The practice was not found to have any influence on the quality of the product at the Brazil plant.

The practice of using cold tundishes does however present some risks for the steel manufacturer since the use of a cold undried tundish could potentially cause premature failure of the dish, which in turn could create catastrophic conditions on the caster. Because of the inherent danger associated with the molten steel that the tundish contains, the decision to attempt using cold tundishes is highly site-specific and cannot be predicted or recommended for all facilities. (AISI, 2011)

At North Star Steel, Iowa, it was estimated that the installation of recuperators for the ladle and tundish heating system would result in fuel savings of 28 percent at the ladle heaters and 26 percent at the tundish dryer. Payback periods were estimated to be from one to 10 years at the time, but have not been verified. (AISI, 2011) While a tundish heater-dryer (capital cost $45,000) annually saves approximately 1,000 MMBtu (1,050 GJ) of natural gas, ladle heaters (capital cost $70,000) save 13,500 MMBtu (14,000 GJ) of natural gas per year. Although general estimates of the fuel savings are difficult to make, one estimate placed potential energy savings at 50 percent, or approximately 0.017 MMBtu/ton (0.02 GJ/tonne) of crude steel.

Near Net Shape Casting

Near net shape casting is a process of casting metal to a form close to that required for the finished product. This means less machining is required to finish the part. Near net shape casting integrates the casting and hot rolling of steel into one process step, thereby reducing the need to reheat the steel before rolling it. Several production processes have been developed for near net shape casting, most notably thin slab casting and strip casting. Thin slab casting and strip casting are both forms of continuous casting.

However, near net shape casting typically can only be used for certain shapes and therefore is not widely applicable to all shapes rolled in the steel industry. Because steelmakers typically manufacture a grade of steel that is used for many different shapes, the steelmaker casts billets that are in a common shape that can be used for many different purposes. This precludes the use of a near shape cast billet for every shape that is rolled of a particular grade. To cast near net shapes for multiple grades of steel could easily create thousands of changes in the casting equipment each year and have a significant impact on the economic viability of an operation. While near net shape casting is viable for some shapes, and in this case greatly reduces energy consumption, for the majority of shapes it is likely to create delays in operations and/or increase operating costs. (AISI, 2011)

In the case of thin slab casting, the steel is cast directly to slabs with a thickness between 1.2 and 2.4 in (30 and 60 mm) instead of slabs with a thickness of 4.72 to 11.8 in (120 to 300 mm). Thin slab casting has been a success in flat product mini-mills in the U.S., and this technology may be a future opportunity for a few more plants that produce thin slabs of steel. Thin slab casting is estimated to reduce energy consumption by 4.2 MMBtu/ton (4.9 GJ/tonne) of crude steel with a payback time of 3.3 years. Investment costs for a large-scale plant were estimated to range from $213/ton ($234.9/tonne) of product with a resultant cost savings of approximately $28/ton ($31/tonne) of crude steel. Another study indicated that thin slab casting with a tunnel furnace offered an energy savings of 0.93 MMBtu/ton (1.08 GJ/tonne) of steel cast.

In strip casting, the steel is cast between two rolls, producing directly a strip of around 0.12 in (3 mm) thickness. Three commercial technologies have emerged in which the steel is cast between two water-cooled casting rolls, which results in very rapid cooling and high production speeds. The major advantage of strip casting is the large reduction in capital costs, due to the high productivity and integration of several production steps. The technology was first applied to stainless steel, and two plants have demonstrated strip casting of carbon steel. One commercial strip casting technology is Castrip®, which was constructed at Nucor's Crawfordsville, Indiana plant in 2002, and since that time the plant has produced Ultra-Thin Cast Strip products. Nucor has also commenced construction of its second strip casting plant in Blytheville, Arkansas. Compared to thick slab casting (hot rolling, pickling and, cold rolling), thin slab casting saves approximately 0.9 MMBtu/ton (1 GJ/tonne). In turn, compared to thin slab casting, the Castrip® process saves approximately another 0.9 MMBtu/ton (1 GJ/tonne). Other strip casting technologies include Eurostrip (developed by a consortium of ThyssenKrupp Steel, Arcelor, and Voest Alpine Industries) and Nippon/Mitsubishi.

Although strip casting leads to considerable capital cost savings and energy savings, it may also indirectly produce energy savings from reduced material losses. Operations and maintenance costs are also expected to drop by 20 to 25 percent, although this will depend strongly on the lifetime of the refractory on the rollers used in the caster and local circumstances. Energy consumption of a strip caster is significantly less than that for continuous casting, with an estimated fuel use of 0.04 MMBtu/ton (0.05 GJ/tonne) and electricity use of 39 kWh/ton (0.15 GJ/tonne). The savings over traditional thick slab continuous casting include 80 to 140 kWh/ton (0.32 to 0.55 GJ/tonne) for electricity and 1.0 to 1.3 MMBtu/ton (1.2 to 1.5 GJ/tonne) for fuel. (Worrell, 2010)

Both thin slab and strip casters are considered by the industry to be product specific and, therefore, are believed to be only viable for new installations and certain products. (AISI, 2011) When there is a good fit between the facility and product, steelmakers say it makes a better product. (Worrell, 2012) Strip casting is becoming increasingly viable, but the products made by this technology have not yet displaced products manufactured in the conventional manner totally. The process creates tradeoffs between more favorable and less favorable material characteristics that should be evaluated for each product. (AISI, 2011)

F. Rolling Mills, General Measures

The semi-finished steel products from the casting operations are further processed to produce finished steel products in a series of shaping and finishing operations in the rolling mills at both Integrated Iron and Steel and EAF plants. Rolling mills are either hot or cold (ambient temperature) processes. Mechanical forces for cold rolling will create much more force and energy needs, while hot rolling happens much faster with less forces; however, there are significant energy costs to heat the metal to near eutectic temperatures.

This section presents energy efficiency measures that are applicable to both the hot rolling and cold rolling processes that could be used at both Integrated Iron and Steel and EAF plants. The sections that follow this general measures section discuss the energy efficiency measures specific to each rolling type.

Energy Efficient Drives

High-efficiency alternating current (AC) motors can save 1 or 2 percent of the electricity consumption of conventional AC drives. Based on an electricity demand of 181 kWh/ton (0.072 GJ/tonne) of rolled steel, the electricity savings were estimated to be 3.6 kWh/ton (0.014 GJ/tonne) of hot rolled steel. The additional cost of a high efficiency drive was estimated to be approximately $0.27/ton ($0.30/tonne) of hot rolled steel. The payback time was estimated as 3.2 years.

The estimated payback time from this study is thought to be specific to the operation at the plant on which the study was based. The payback period of these drives is thought to be highly variable, in that it can be significantly longer or even shorter depending upon the many variables involved. (AISI, 2011)

Gate Communicated Turn-Off Inverters

Drive units for main equipment such as rolling mills in steel plants use variable-speed AC operation. As switching devices for large-capacity inverted drives, Gate Turn-Off thyristors have been widely used. However, a Gate Communicated Turn-Off thyristor can be used instead of a Gate Turn-Off thyristor to decrease switching losses. Compared with this Gate Turn-Off the Gate Communicated Turn-Off inverter has higher system efficiency, not only at rated-load operation, but also at light-load operation and reduces energy loss. The Gate Communicated Turn-Off inverters are typically used to drive steel rolling mills and are being adopted in every area of steel mills from high-speed wire rolling to low-speed cold rolling. Moreover, they are applicable as energy-saving drive units for large-capacity fans, pumps, and compressors.

G. Hot Rolling Mills

This section presents energy efficiency measures that are specific to hot rolling that could be used at both Integrated Iron and Steel and EAF plants. Measures for cold rolling processes follow and general measures for both hot and cold rolling are above.

In any hot rolling operation, the reheating furnace is a critical factor to determine end-product quality, as well as to total costs of the operation. Energy use in a reheating furnace depends on production factors (e.g., stock, steel type), operational factors (e.g., scheduling), and design features. Savings may be achieved through optimized processes and by upgrading existing furnaces. The upgrade of a reheat furnace of North Star Steel (Iowa) led to significant fuel, energy cost and labor savings together with savings due to the reduction of scrap use while furnace refractory life and product quality improved.

Proper Reheating Temperature

In choosing the heating temperature for semi-finished products prior to rolling, an attempt should be made to obtain a fine-grained structure in the metal along with the requisite mechanical properties in the rolled product. The heating operation should also ensure dissolution of the inclusions in the metal in the absence of excessive grain growth. A reduction of the heating temperature by 212°F (100°C) decreases unit fuel consumption by 9 to 10 percent. However, lowering the heating temperature will increase the rolling forces and moments, and hence increase the load on the electric drive motors, i.e., it will have the overall effect of increasing the mechanical and electrical loads on the main components of the mill, thereby increasing energy consumption and wear of the mill equipment. (Worrell, 2009) Since there are many permutations that arise from the combination of rolling equipment, temperature, steel grade, desired end shape, cooling water temperature, etc., it is considered difficult to address the specific energy gains that can be made by varying heat levels. (AISI, 2011) As a result, under certain conditions total unit energy consumption may not decrease with a decrease in heating temperature (even without allowance for the losses associated with electric power generation). Therefore, any changes to the heating temperature first should be examined using a systems approach. (Worrell, 2009)

Avoiding Overload of Reheat Furnaces

Overloading a furnace can lead to excessive stack temperatures. To get the proper rate of heat transfer, combustion gases must remain in the heating chamber for the right amount of time. The natural tendency of an overloaded furnace is to run colder than optimal, unless the temperature is set artificially high. This causes the burners to operate at higher than normal firing rates, which increases combustion gas volumes. The higher gas flow rates and shorter time that the gas remains in the furnace causes poor heat transfer, resulting in higher temperatures of the flue gases. The increased volumes of higher temperature flue gases lead to sharply increased heat losses. Overly ambitious production goals might be met, but at the cost of excessive fuel consumption. The overload problem may be corrected by improving heat transfer or not operating in this mode to achieve ambitious production goals.

Because most reheat furnaces are regulated by the amount of and type of fuel that they can consume, overloading is thought to be a very rare event. Overloading a reheat furnace with billets will typically reduce mill production rates and is not considered an economical operation in the long term. Overloading with respect to the fuel feed can cause increased emissions from the furnace, which is also undesirable, and a prohibited operating condition for most facilities. (AISI, 2011)

Hot Charging

Hot charging is the process of heating slabs prior to charging them into the reheating furnace of the hot mill. The higher the preheat temperature, the greater the energy savings in the hot mill furnace. The layout of the plant will affect the feasibility of hot charging because the caster and reheating furnace should be located in proximity to one another to avoid a long, hot connection pathway between the two.

However, even if a facility would prefer to hot charge, the ability to do so is limited. When the meltshop or the roll mill has services interrupted, the entire facility operations are disrupted if there is no longer a break period between the melting and rolling operations. This can offset the advantages of energy savings. (AISI, 2011)

Although actual savings will be highly plant dependent, one estimate of the potential energy savings was as much as 0.05 MMBtu/ton (0.06 GJ/tonne) of hot charged steel. Investment costs were estimated to be approximately $21.3/ton ($23.5/tonne) of hot rolled steel, with annual cost savings of up to $1.04/ton ($1.15/tonne) of hot charged steel and a payback time of 5.9 years.

Process Control in Hot Strip Mill

Improved process control of the hot strip mill may lead to indirect energy savings through reduced product rejects, improved productivity, and reduced down time. This measure includes controlling oxygen levels and VSDs on combustion air fans, which both help to control the oxygen level, and hence optimize the combustion in the furnace, especially as the load of the furnace may vary over time. The savings depend on the load factor of the furnace and control strategies applied. A system installed at ArcelorMittal's Sidmar plant (Belgium) reduced the share of rejects from 1.5 to 0.2 percent and reduced the downtime from more than 50 percent of the time to 6 percent. Estimated energy savings based on reduced rejects was 9 percent of fuel use, or approximately 0.26 MMBtu/ton (0.3 GJ/tonne) of product. The investment costs for one plant in Belgium was

$3.6 million for a hot strip mill with a capacity of 3.1 million tons (2.8 million tonnes), or approximately $1.20/ton ($1.29/tonne) of product. The payback time is estimated as 1.2 years.

Recuperative Burners

Application of recuperative or regenerative burners can substantially reduce energy consumption. A recuperator is a gas-to-gas heat exchanger placed on the stack of the furnace. There are numerous designs, but all rely on tubes or plates to transfer heat from the outgoing exhaust gas to the incoming combustion air, while keeping the two streams from mixing. Recuperative burners use the heat from the exhaust gas to preheat the combustion air. Recuperative burners can reduce fuel consumption by 10 to 20 percent compared to furnaces without heat recovery.

Since modern recuperative or regenerative burner systems can have significantly higher efficiencies than older systems, savings can also be attained by replacement of old or aging recuperative or regenerative burners. Newer designs can also have lower NO_x emissions; consequently, the evaluation of recuperative or regenerative burner systems should include an assessment of the impact on NO_x emissions. Replacement of the recuperator by a newer model can result in substantial savings as is illustrated by an example at North Star Steel (Iowa). Recuperator replacement at this plant was estimated to achieve fuel savings of 9 percent with an expected payback period of 6 months. Another example in Japan shows that a newer model continuous slab reheating furnace can reduce energy consumption by 25 percent in comparison to an older furnace recovering waste heat with a recuperator.

Recuperative burners in the reheating furnace can reduce energy consumption by as much as 30 percent. Although actual savings will be highly facility-specific, one estimate placed energy savings at approximately 0.6 MMBtu/ton (0.7 GJ/tonne) of product, with an investment cost of approximately $3.5/ton ($3.9/tonne) of product. The payback time is estimated as 1.8 years.

Although recuperative burner use is common at many facilities, these burners are regulated via the air permit system due to their potential to create NOx emissions at higher flame temperatures. Therefore, the potential energy efficiency improvements through the use of recuperative burners would be limited unless permit conditions are modified. (AISI, 2011)

Flameless Burners

A widely used technique to enhance furnace efficiency is extensive air preheating, but the drawback is a parallel increase of NO_x emissions. Another technique is the use of flameless burners. Flameless air-fuel combustion uses air as oxidizer, while flameless oxy-fuel uses commercial oxygen as an oxidant. This technology carries out combustion under diluted oxygen conditions using internal flue gas recirculation and the flame becomes invisible. Flameless oxy-fuel gives high thermal efficiency, higher levels of heat flux, and reduced fuel consumption compared to conventional oxy-fuel. These benefits are combined with low NO_x emissions and better thermal uniformity. Since 2003, more than 30 furnaces within the U.S. steel industry have been equipped with flameless oxy-fuel combustion.

ArcelorMittal recently received the Association for Iron & Steel Technology (AIST) 2009 Energy Achievement Award for its work to implement a flameless oxy-fuel operation on its rotary-hearth steel-reheat furnace. ArcelorMittal realized a 60 percent reduction in the furnace's total fuel consumption compared to the original air-fuel operation. The technology also reduced the furnace's annual NO_x emissions output by 92 percent and annual CO_2 emissions by up to 60 percent below the prior air-fuel operating levels. The conversion also enabled

ArcelorMittal to achieve a 25 percent increase in material throughput and a 50 percent reduction in scale formation (R&D Magazine, 2010).

This technology is commonly used in the EAF industry but, as with recuperative burners above, the use of fameless burners is limited by permit to keep the preheat air temperature below 900^{o}F so as to lower the rate of NOx formation. Permit modifications also would be needed with this technology to implement this strategy to reduce energy. (AISI, 2011)

Insulation of Furnaces

Replacing conventional insulating materials with ceramic low-thermal–mass insulation materials can reduce the heat losses through furnace walls. The potential energy savings for insulating a continuous furnace were estimated to range from 2 to 5 percent, or approximately 0.14 MMBtu/ton (0.16 GJ/tonne) of product. Capital costs were estimated to be $14.1/ton ($15.6/tonne) of product. The payback time is estimated as 31 years.

Walking Beam Furnace

A walking beam furnace represents the state-of-the-art of efficient reheating furnaces. In a walking beam furnace, the stock is placed on stationary ridges and a revolving beam walks the product along through the furnace until the exit where the beam returns to the furnace entrance. WCI Steel has a walking beam furnace that also employed a state-of-the-art combustion control. The use of this furnace at WCI Steel resulted in a reduction in electricity usage by 25 percent per ton produced and a reduction in overall fuel consumption by 37.5 percent per ton produced compared to three pusher-type furnaces.

Controlling Oxygen Levels and Variable-Speed Drives on Combustion Air Fans

Controlling oxygen levels and using VSDs on the combustion air fans on the reheating furnace helps to optimize combustion in the furnace. Excess air can substantially decrease combustion efficiency as it leads to excessive waste gases. Fuel-air ratios of the burners should therefore be checked regularly. The use of VSDs on combustion air fans on the reheating furnace also helps to control the oxygen level, especially as the load of the furnace may vary over time. The savings depend on the load factor of the furnace and the control strategies applied. Implementing a VSD on a combustion fan of a walking beam furnace at Cardiff Rod Mill (UK) reduced the fuel consumption by 48 percent and had a payback period of 16 months. Energy savings can vary widely depending on the specific installation, but one conservative estimate place the savings at 10 percent, or approximately 0.28 MMBtu/ton (0.33 GJ/tonne) of product. The estimated investment costs were $0.72/ton ($0.79/tonne) of product. The payback time is estimated as 0.8 years.

Heat Recovery to the Product

In cases that it is not possible to hot-charge the slabs directly from the caster, energy can be recovered bringing exhaust gases that leave the high temperature portion of the process into contact with the relatively cool slabs. This will preheat the slab charge. In a plant-wide assessment of North Star Steel (Iowa) it was estimated that using furnace flue gases to preheat the charge to a moderate temperature of 840 to 1,020°F (450 to 550°C) would result in costs savings of about 32 percent. Another study reports a 50 percent reduction of the unit energy consumption of a heating furnace when charging semi-finished products at a temperature above 1,200°F (650°C) and a 70 to 80 percent reduction at charging temperatures above 1,800°F (980°C).

Waste Heat Recovery from Cooling Water

Waste heat can be recovered from the hot strip mill cooling water to produce low-pressure steam. Estimated fuel savings are 0.034 MMBtu/ton (0.04 GJ/tonne) of product, with a required increase in electricity consumption of 0.15 kWh/ton (0.0006 GJ/tonne) of product. Investment costs were estimated to be $1.2/ton ($1.3/tonne) of product. Operating and maintenance costs may increase by $0.10/ton ($0.11/tonne) of product. The payback time is estimated at over 50 years.

H. Cold Rolling Mills

This section presents energy efficiency measures that are specific to cold rolling that could be used at both Integrated Iron and Steel and EAF plants. Measures for hot rolling processes and general measures for both hot and cold rolling are above.

Heat Recovery on the Annealing Line

Heat recovery can be accomplished by generating steam from recovered waste heat or by installing recuperative or regenerative burners in the annealing furnace. By instituting several measures to recover heat, including regenerative burners, insulation improvement, process management, and VSDs, energy consumption can be reduced by as much as 40 percent. This equates to an energy savings of approximately 0.26 MMBtu/ton (0.3 GJ/tonne) and 2.7 kWh/ton (0.011 GJ/tonne). Investment costs were estimated to be $3.8/ton ($4.2/tonne) based on one mill in The Netherlands. The payback time is estimated as 4 years.

Reduced Steam Use in the Pickling Line

Lids and/or floating balls can be added to the heated hydrochloric acid bath in the pickling line to reduce evaporation losses. Energy savings of up to 17 percent, or approximately 0.16 MMBtu/ton (0.19 GJ/tonne), have been estimated. Estimated capital costs were $4.0/ton ($4.4/tonne) of product. The payback time is estimated as 7 years.

Automated Monitoring and Targeting System

Power demands on the cold strip mill can be reduced by installing an automated monitoring and targeting system to improve operating efficiency. A system installed at one British steel mill reduced the energy demand of the cold rolling mill by approximately 15 to 20 percent, or approximately 54 kWh/ton (0.22 GJ/tonne). Installation costs were estimated to be $1.56/ton ($1.72/tonne) of product, or $0.92/ton ($1.0/tonne) of crude steel. The payback time is estimated as 0.8 years.

I. Finishing Operations

This section presents energy efficiency measures for finishing operations that could be used at both Integrated Iron and Steel and EAF plants.

Inter-Electrode Insulation in Electrolytic Pickling Line

The existing industrial electrolytic steel pickling process is only 30 percent current efficient. This efficiency can be increased by reducing inter-electrode short circuit current with inter-electrode isolation. Experiments have shown that the current efficiency of the process is improved from 20 percent without insulation to 100 percent with it. Complete insulation does, however, lead to sludge accumulation in the compartments where the steel band is anodic, resulting in an inhomogeneous electrolyte and higher maintenance requirements. Use of an insulation which covers less than 66 percent of the electrolyte cross section area between the anode and cathode electrode groups offers a compromise as it results in a significant improvement in the process efficiency while maintaining good circulation and homogeneity of the electrolyte solution. The method is relatively easily applicable as a retrofit. No cost information was available in the original reference.

Continuous Annealing

A continuous annealing furnace makes it possible to integrate the conventional batch annealing process (i.e., electrolytic cleaning - annealing - cooling - temper rolling - recoiling) into one line. The use of such a furnace can lead to significant energy saving and productivity. For instance, for a particular continuous annealing furnace, the annealing time for one roll is approximately 30 minutes, as compared to approximately 10 days for the conventional bath process. In addition, fuel consumption is reduced by about 33 percent.

Considerable differences in fuel consumption exist between different types of cooling equipment used in continuous annealing: the suction cooling roll uses only 14 percent of the power used by a gas jet system. The installation of continuous annealing equipment demands relatively high investment costs. For example, a new (to be constructed) continuous annealing facility with a capacity of about 500,000 tpy (450,000 tonnes/year) in the Midwest has an estimated cost of $225 million. No information was available for payback time.

J. General Measures for Energy Efficiency Improvements

This section presents general energy efficiency measures that could be used at both Integrated Iron and Steel and EAF plants.

Preventive Maintenance

Training programs and good housekeeping programs help to decrease energy consumption throughout the plant. Some estimates place the energy savings at 2 percent of total energy use, or a fuel savings of approximately 0.39 MMBtu/ton (0.45 GJ/tonne) of product and an electricity savings of approximately 0.034 MMBtu/ton (0.04 GJ/tonne) of product. One estimate of annual operating costs was $16,600 per plant, or approximately $0.018/ton ($0.02/tonne) of crude steel.

Energy Monitoring and Management System

Energy monitoring and management systems help provide for optimal energy recovery and distribution between processes at the plant. These systems may reduce energy consumption by 0.5 percent, or fuel savings of approximately 0.10 MMBtu/ton (0.12 GJ/tonne) of product and electricity savings of approximately 0.0086 MMBtu/ton (0.01 GJ/tonne) of product. Based on a system installed at one plant in The Netherlands, the cost of a monitoring and management system was approximately $0.21/ton ($0.23/tonne) of crude steel based on an investment cost of $1.2 million. The payback time is estimated as 0.5 years.

Combined Heat and Power/Cogeneration

All steel plants require both electricity and steam to operate, which make them good candidates for combined heat and power (CHP), also known as cogeneration. Modern CHP systems can be based on gas turbines with a waste heat recovery boiler, combined cycles that integrate a gas turbine with a steam turbine for larger systems, or high pressure steam boilers (both fuel-fired or waste heat boilers) coupled with a steam turbine generator. The type and size of CHP system utilized depends on a variety of site-specific factors including the amount and quality of off-gases from the coke oven, blast furnace, and BOF; the steam requirements of the facility, and the economics of generating power on-site versus purchasing power from the grid. CHP capital costs can range from $900 to $2,500/kW depending on size and technology. (EPA, 2007b) Estimates range from $20.6/ton ($22.7/tonne) of crude steel. The payback time is estimated as 6 years. Over thirty steel and Coke plants have currently installed CHP systems. (ICF, 2010) The newest Coke plants all recover the heat from the battery stack to produce steam and/or electricity. Most Integrated Iron and Steel plants use excess process fuel gases (BFG and COG) for CHP units.

A significant barrier to CHP development and deployment is thought to be due to local electric utility company policies to restrict their use. These policies would need to be addressed on a case-by-case basis before CHP could be implemented. (AISI, 2011)

High-Efficiency Motors

Due to the high number of motors at an Iron and Steel plant, a systems approach to energy efficiency should be considered. Such an approach should look for energy efficiency opportunities for all motor systems (e.g., motors, drives, pumps, fans, compressors, controls). An evaluation of energy supply and energy demand should be performed to optimize overall performance. A systems approach includes a motor management plan that considers at least the following factors:

- Strategic motor selection;
- Maintenance;
- Proper size;
- Adjustable speed drives;
- Power factor correction; and
- Minimize voltage unbalances.

One estimate of overall energy consumption by motors in the steel industry was 22 billion kWh. DOE has estimated that 12 percent of this energy could be saved through the use of more efficient equipment. One estimate places the potential energy savings from motor efficiency improvements at 0.3 MMBtu/ton (0.35 GJ/tonne). (Stubbles, 2000) Payback time is estimated as 1 to 3 years.

Motor management plans and other efficiency improvements can be implemented at existing facilities and should be considered in the design of new construction.

K. Energy Efficiency Options for Electric Arc Furnace Steelmaking

Opportunities to improve energy efficiency specific to EAF steelmaking facilities are described below. The energy efficiency measures for casting, rolling, and other finishing processes at EAF facilities are the same as for Integrated Iron and Steel mills described above and in **Table 1**. Energy efficiency opportunities specific to EAF facilities are discussed in the following sections and are included in **Table 2**.

Improved Process Control (Neural Networks)

Process control can optimize operations and thereby significantly reduce electricity consumption as is demonstrated by many examples worldwide. Modern controls which use a multitude of sensors can help to achieve this to a greater extent than older controls. Control and monitoring systems for EAF are moving towards integration of real-time monitoring of process variables, such as steel bath temperature, carbon levels, and distance to scrap, along with real-time control systems for graphite injection and lance oxygen practice. As an example, neural networks systems analyze data and emulate the best controller and can thus help to reduce electricity consumption beyond that achieved through classical control systems. Neural networks can help achieve additional reductions in energy consumption over classic control systems. For EAF, average power savings were estimated to be 8 percent, or 34.5 kWh/ton (0.14 GJ/tonne). Additionally, productivity increased by 9 to 12 percent, and electrode consumption was reduced by 25 percent. Capital costs were estimated to be $372,500 per furnace, with annual cost savings of approximately $1.4/ton ($1.5/tonne). The payback time is estimated as 0.5 years.

By monitoring the furnace exhaust gas flow rate and composition, the use of chemical energy in the furnace can be enhanced. Detailed investigation of the post-combustion of off-gases can be carried by an optical sensor. Using the monitored data as input for a control system, post-combustion of off-gases can be controlled online. Benefits of this practice include reduced electricity consumption, shorter power-on times, increased productivity, a decrease in production costs, a reduction of electrode consumption, reduced natural gas, oxygen and carbon consumption, and a reduction of refractory wear. It has been demonstrated that, if oxygen injected for post-combustion is continuously controlled by real-time data acquisition of CO and CO_2 concentrations in off-gases, a 50 percent increase in recovery rate of chemical energy in fumes can be achieved compared to operation based on predefined set-points.

A specific system that continuously measures CO, CO_2, H_2, and O_2 to control post-combustion was installed at the Hylsa’s Planta Norte plant near Monterrey (Mexico) and by Nucor, Seattle (WA). The system led to reductions of 2 percent and 4 percent in electricity consumption, 8 percent and 16 percent in natural gas consumption, 5 percent and 16 percent in oxygen use, 18 percent and 18 percent in carbon charged and injected. At the same time, yield improved (between 1 percent and 2 percent), and electrode consumption decreased (3.5 percent and 16 percent), while productivity increased by 8 percent.

Although neural network manufacturers’ claims of efficiency gains are impressive, industry representatives believe it is possible to achieve the same improvement with a well-managed energy system run by a well-trained operator. With the proper tools to measure the furnace operating parameters, which may include electronic monitoring devices much simpler than neural networks, a well-trained operator may be capable of meeting or exceeding the performance of a computer system at a lower cost. (AISI, 2011) Any approach that can produce similar energy savings, reductions in electricity consumption, and reductions in fuel use in a payback time of less than a year should be encouraged.

Adjustable Speed Drives

As flue gas flow varies over time, adjustable speed drives offer opportunities to operate dust collection fans in a more energy efficient manner energy can. Flue gas adjustable speed drives have been installed in various countries (e.g., Germany, UK). The electricity savings are estimated to be 15 kWh/ton (0.06 GJ/tonne), with a payback period of 2 to 3 years. Although dust collection rates were reduced by 2 to 3 percent, total energy usage decreased by 67 percent. Capital costs were estimated to be $1.8/ton ($2/tonne). The payback time is estimated as 2 to 3 years.

Transformer Efficiency—Ultra-High–Power Transformers

Ultra-high–power (UHP) transformers help to reduce energy loss and increase productivity. The UHP furnaces are those with a transformer capacity of more than 700 kilovolt amps (kVA)/tonne heat size. The UHP operation may lead to heat fluxes and increased refractory wear, making cooling of the furnace panels necessary. This results in heat losses that partially offset the power savings. Total energy savings were estimated to be 15 kWh/ton (0.061 GJ/tonne). Many EAF operators have installed new transformers and electric systems to increase the power of the furnaces, e.g., Co-Steel (Raritan, NJ), SMI (Sequin, TX), Bayou Steel (Laplace, LA), and Ugine Ardoise (France). Capital costs were estimated to be \$3.9/ton (\$4.3/tonne). The payback time is estimated as 5.2 years.

Bottom Stirring/Stirring Gas Injection

Bottom stirring is accomplished by injecting an inert gas into the bottom of the EAF to increase the heat transfer in the melt. In addition, increased interaction between slag and melt leads to an increased liquid metal yield of 0.5 percent. Furnaces with oxygen injection are sufficiently turbulent, reducing the need for inert gas stirring. The increased stirring can lead to electricity savings of 10 to 20 kWh/ton (0.04 to 0.08 GJ/tonne), with net annual production cost reduction of \$0.72 to \$1.4/ton (\$0.8 to \$1.6/tonne). Taking into account the increased liquid steel yield may increase the cost savings to \$1.3 to \$3.1/ton (\$1.4 to \$3.4/tonne). Power savings were estimated to be 18 kWh/ton (0.072 GJ/tonne). Capital costs for retrofitting existing furnaces were estimated to be \$0.85/ton (\$0.94/tonne) for increased refractory costs and installing tuyeres, and annual costs for inert gas purchase was estimated to be \$1.8/ton (\$2.0/tonne). Productivity increases were estimated to reduce costs by \$5.0/ton (\$5.5/tonne). The payback time is estimated as 0.2 years.

Foamy Slag Practice

Foamy slag covers the arc and melt surface to reduce radiation heat losses. Foamy slag can be obtained by injecting carbon (granular coal) and oxygen or by lancing of oxygen only. Slag foaming increases the electric power efficiency by at least 20 percent in spite of a higher arc voltage. The net energy savings (accounting for energy use for oxygen production) are estimated at 5 to 7 kWh/ton (0.02 to 0.028 GJ/tonne) steel. Foamy slag practice may also increase productivity through reduced tap-to-tap times. Investment costs are about \$14.1/ton (\$15.6/tonne) capacity. Productivity increases may be equivalent to a cost savings of approximately \$2.6/ton (\$2.9/tonne) steel. The payback time is estimated as 4.2 years.

Oxy-Fuel Burners

Oxy-fuel burners are used on most EAF in the U.S. (AISI, 2011) These burners increase the effective capacity of the furnace by increasing the speed of the melt and reducing the consumption of electricity and electrode material, which reduces GHG emissions.

The use of oxy-fuels burners has several other beneficial effects: it increases heat transfer, reduces heat losses, reduces electrode consumption and, and reduces tap-to-tap time. Moreover, the injection of oxygen helps to remove different elements from the steel bath, like phosphorus, silicon and carbon. Steelmakers are now making wide use of stationary wall-mounted oxygen-gas burners and combination lance-burners, which operate in a burner mode during the initial part of the melting period. When a liquid bath is formed, the burners change over to a mode in which they act as oxygen lances. Electricity savings may range from 88 to 155 kWh/ft^3 (11 to 20 GJ/m^3) oxygen injected. Natural gas injection is typically 10 standard cubic feet per kilowatt hour, with energy savings ranging from 18 to 36 kWh/ton (0.72 to 0.14 GJ/tonne). Investment cost for modifying a 121 ton (110 tonne) EAF were estimated to be $6.8/ton ($7.5/tonne). Annual cost savings may be approximately $6.4/ton ($7.1/tonne) due to reduced tap-to-tap times. The payback time is estimated as 0.9 years.

Post-combustion of the Flue Gases

Post-combustion is a process for utilizing the chemical energy in the CO and hydrogen evolving from the steel bath to heat the steel in the EAF ladle or to preheat scrap to 570 to 1,470°F (300 to 800°C). It reduces electrical energy requirements and increases the productivity of the EAF. Other benefits include reduction of baghouse emissions, reduction of the temperature of the off-gas system and minimization of high temperature spikes associated with rapid CO evolution. Post-combustion helps to optimize the benefits of oxygen and fuel injection. EAF operations that involve large amounts of charged carbon or pig iron are particularly suitable for implementation of CO post-combustion technology during scrap melting.

It is critical that post-combustion is done early at melt down while the scrap is still capable of absorbing the evolved heat. The injectors should be placed low enough to increase CO retention time in the scrap in order to transfer its heat. The oxygen flow should have a low velocity to promote mixing with the furnace gases and avoid both scrap oxidation and oxygen rebound from the scrap to the water cooled panels. The injectors should also be cooled extremely well as the post combustion area often gets overheated. In order to distribute the chemical energy uniformly and to make its utilization efficient, it is preferable to bifurcate the post combustion oxygen flow and to space out the injectors in the colder areas of the shell. For a particular post-combustion system, electricity savings ranged from 6 to 11 percent and reductions in tap-to-tap time from 3 to 11 percent, depending on the operating conditions. No information was available for costs or payback time.

This technology is commonly used in the U.S. and is considered to be the best control technology for CO emissions. (AISI, 2011)

Direct Current Arc Furnace

The direct current (DC) arc furnace was pioneered in Europe, and these single-electrode furnaces with DC rather than alternating current (AC) have been used in North America for over 20 years. This technology is considered to be limited to new installations because of the prohibitive scale of the retrofit costs. (AISI, 2011)

In a DC furnace, one single electrode is used, and the bottom of the vessel serves as the anode. Based on the distinctive feature of using the heat and magnetic force generated by the current in melting, this arc furnace achieves an energy saving of approximately 5 percent in terms of power unit consumption in comparison with the 3-phase AC arc furnace. In addition, it also has other features, including higher melting efficiency and extended hearth life. Power consumption is 454 to 544 kWh/ton (1.8 to 2.2 GJ/tonne) molten steel. Electrode consumption is about half that with conventional furnaces. This corresponds to 2.4 to 4.9 lb/ton (1 to 2 kg/ tonne) molten steel. This measure is applied to large furnaces only. Net energy savings were estimated to be 82 kWh/ton (0.32 GJ/tonne). However, compared to new AC furnaces, the savings are limited to 9 to 18 kWh/ton (0.036 to 0.072 GJ/tonne). The additional investment costs over that of an AC furnace are approximately $5.5/ton ($6.1/tonne) capacity. The payback time is estimated as 0.7 years.

The design of the DC arc furnace also reduces noise and electrical flicker, increases efficiency, and reduces electrode consumption. As of 2007, there are eight DC powered EAF operating in the U.S. and one in Mexico; most of these EAF have been installed in the past 2 years, with the oldest installed in 1991. The manufacturers involved are Fuchs, NKK/United, MAN GHH, and Voest-Alpine. Facilities that are currently using this new technology include Charter Steel, Florida Steel, Gallatin Steel, North Star Steel, and many Nucor plants (e.g., Blytheville, AR; Berkeley, SC; Decatur, AL; Hertford, NC; Norfolk, NE; Darlington, SC).

Scrap Preheating

Scrap preheating is performed either in the scrap charging baskets, in a charging shaft (shaft furnace) added to the EAF, or in a specially designed scrap conveying system allowing continuous charging during the melting process. Scrap preheating is used extensively in Japan, and the use of hot furnace gases for scrap preheating is now being applied in the U.S. Scrap preheating can save 4 to 50 kWh/ton (0.016 to 0.20 GJ/tonne) and reduce tap-to-tap times by 8 to 10 minutes. A prominent example of its application to new EAF with continuous charging is the Consteel process, which is being used at Gerdau-Ameristeel plants in Charlotte, NC, Knoxville, TN, and Sayreville, NJ; and at Nucor plants in Darlington, SC, and Hertford, NC.

Preheating scrap reduces the power consumption of the EAF by using the waste heat of the EAF as the energy source for the preheat operation. The Consteel process consists of a conveyor belt that transports the scrap through a tunnel to the EAF. In addition to energy savings, the Consteel process can increase productivity by 33 percent, decrease electrode consumption by 40 percent, and reduce dust emissions. Electricity savings can be 54 kWh/ton (0.22 GJ/tonne), and investment costs were estimated to be $3.2 million for a capacity of 550,000 tpy (500,000 tonne/yr) or $7.1/ton ($7.8/tonne) of product. Annual costs savings were estimated to be $2.7/ton ($3.0/tonne). The payback time is estimated as 1.3 years. Unless electricity is generated on-site, the GHG reductions will be indirect, i.e., at the power plant.

Because scrap preheating exposes the scrap metal to temperatures much lower than in the EAF for extended periods of time, increased emissions of some criteria pollutants, such as volatile organic compounds (VOC), are thought to be possible. The VOC emissions are commonly fully combusted in the EAF off gas system. In the case of Consteel, they are also created in the off gas system. (AISI, 2011)

Scrap Preheating, Post Combustion—Shaft Furnace (Fuchs)

Shaft-furnace technology (both single- and double-shaft furnaces) was pioneered by Fuchs in the late 1980s. Since 2005, the VAI Fuchs furnace has been known as SIMETALCIS EAF. With the single shaft furnace, up to 70 kWh/ton (0.28 GJ/tonne) liquid steel of electric power can be saved. The finger shaft furnace[7] allows energy savings up to 100 kWh/ton (0.40 GJ/tonne) liquid steel, which is about 25 percent of the overall electricity input into the furnace. The exact energy savings depend on the scrap used, and the degree of post-combustion (oxygen levels). For the finger shaft furnace tap-to-tap times of about 35 minutes are achieved, which is about 10 to 15 minutes less compared to EAF without efficient scrap preheating. The process may reduce electrode consumption, improve yield by 0.25 to 2 percent, increase productivity by 20 percent, and decrease flue gas dust emissions by 25 percent. Retrofit costs were estimated to be $8.5/ton ($9.4/tonne) for an existing 110-ton (100-tonne) furnace. Production cost savings may amount to $6.1/ton ($6.7/tonne). The payback time is estimated as 1 year.

It should be noted that these EAF operations have demonstrated a propensity to emit high volumes of CO. (AISI, 2011)

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[7] The most efficient shaft-furnace design is the finger-shaft furnace, which employs a unique scrap retaining system with fingers to preheat 100 percent of the scrap charge using the hot flue gases.

Engineered Refractories

Refractories in EAF have to withstand extreme conditions such as temperatures over 2,900°F (1,600°C), oxidation, thermal shock, erosion and corrosion. These extreme conditions generally lead to an undesired wear of refractories. Refractories can be provided by a controlled microstructure: alumina particles and mullite microballoons coated uniformly with carbon and carbides. The refractories can be either sintered or cast and can therefore be used in a wide range of components at EAF mills (e.g., furnace, ladle furnace, vessels). The refractories can reduce ladle leakages and the formation of slag in transfer operations with savings of 10 kWh/ton (0.04 GJ/tonne) steel.

Airtight Operation

A large amount of air enters the EAF: around 1,000,000 ft^3 (30,000 m^3) in a standard EAF of 165 tons (150 tonnes) of steel with a heat duration of 1 hour. This air is at ambient temperature, and the air's nitrogen and non-reactive oxygen are heated in the furnace and exit with the fumes at high temperature (around 1,800°F) (980°C), resulting in significant thermal losses. Based on the results of pilot scale trials with a 7 ton (6 tonne) EAF at Arcelor Research, the potential benefit for an industrial furnace with an airtight process including a post-combustion practice and an efficient fume exhaust control is about 100 kWh/ton (0.4 GJ/tonne) for an industrial furnace having a current electric consumption of 450 kWh/ton (1.8 GJ/tonne). About 80 percent of the savings can be attributed to a reduction of energy losses in the fumes. The remaining 20 percent are accounted for by reduced thermal losses due to a reduced tap-to-tap time. The exhaust gas can be used as a fuel in the post-combustion chamber, which reduces the amount of natural gas needed for the burner.

The primary reason for failure to operate an airtight EAF is the need to evaluate the material within the EAF continuously while charging the EAF with scrap, and then also balancing the requirement to control emissions from the EAF. This operational complexity is compounded by the fact that the scrap metal is highly variable and will have varied degrees of density that will require varying degrees of energy as the scrap density changes. While the EAF operator can attempt to control these variables, the limitations of optimizing the process are driven more by the variation in the scrap supply than anything else. The complexity is further increased if in an effort to maintain compliance, the operator is biased toward higher evacuation rates. This offsets some of the gains to be made toward better energy efficiency since more energy is used per unit time as the evacuation flow is increased. It is necessary to find a balance between air tightness, scrap density, and access to the furnace for sampling the metal. Complete air tightness will never be achieved, but incremental improvements might be gained in these efforts. (AISI, 2011)

Contiarc® Furnace

The *Contiarc* furnace is fed continuously with material in a ring between the central shaft and the outer furnace vessel, where the charged material is continuously preheated by the rising process gas in a counter-current flow, while the material continuously moves down. Located below the central shaft is a "free-melting volume" in the form of a cavern. Advantages of the Contiarc furnace include (1) reduced energy losses (200 kWh/ton or 0.8 GJ/tonne less than with conventional furnace systems), (2) waste gas and dust volumes are considerably reduced, which results in a lower capacity for the gas cleaning system and also lower electric power consumption (23 kWh/ton or 0.091 GJ/tonne), (3) gas-tight furnace enclosure captures all primary and nearly all secondary emissions, and (4) reduced electrode consumption (about 1.8 lb/ton or 0.9 kg/tonne less than a typical AC furnace).

Flue Gas Monitoring and Control

The use of VSDs can reduce energy usage of the flue gas fans, which in turn reduces the losses in the flue gas. Electricity savings were estimated to be 13.6 kWh/ton (0.054 GJ/tonne) with a payback period of 2 to 4 years. Capital costs were estimated to be $2.8/ton ($3.1/tonne). However, in practice, these systems have proven to be of limited utility since continuous emissions monitoring systems provide a substantial amount of information for EAF operators that includes most of the information that VSD systems provide. Operators have found that VSD systems are not able to predict problems that occur in EAF due to the variability in the scrap and also from energy fluctuations. These factors effect EAF emissions and the ability of the facility to meet emission regulations. (AISI, 2011)

Eccentric Bottom Tapping

Eccentric bottom tapping leads to slag-free tapping, shorter tap-to-tap times, reduced refractory and electrode consumption, and improved ladle life. Energy savings were estimated to be 13.6 kWh/ton (0.054 GJ/tonne). Modification costs for a Canadian plant were $3.3 million for a furnace with an annual production capacity of 760,000 tons (690,000 tonnes) or $4.5/ton ($5.0/tonne). The payback time is estimated as 7 years.

Twin-Shell Furnace

A twin-shell furnace includes two EAF vessels with a common arc and power supply system. The system increases productivity by decreasing tap-to-tap time, and reduces energy consumption by reducing heat losses. A twin-shell furnace may save 17 kWh/ton (0.068 GJ/tonne) compared to a single-shell furnace. Production costs are expected to be $1.8/ton ($2.0/tonne) lower that a single-shell furnace, and the investment costs are expected to be approximately $8.5/ton ($9.4/tonne) over that of a single-shell furnace. The payback time is estimated as 3.5 years.

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Appendix A. Emerging Techniques for GHG Control

A.1 Long-Term Opportunities to Reduce CO_2 Emissions (Worrell, 2009)

The global steel industry collaborates in the ULCOS project to find opportunities to dramatically reduce CO_2 emissions from iron and steelmaking. ULCOS is a consortium of 48 European companies and organizations from 15 European countries that have launched a cooperative R&D initiative to enable drastic reduction in CO_2 emissions from steel production. The aim of the ULCOS program is to reduce the CO_2 emissions by at least 50 percent.

ULCOS has selected four process concepts that could lead to a reduction of CO_2 emissions by more than half compared to current best practice. The following are the four breakthrough technologies identified:

- Electrolysis;
- HIsarna with CCS; and
- Carbon capture and storage (CCS)

Electrolysis, which leads directly to final products, is to be compared to a whole conventional mill, which has an energy consumption of 15 to 20 GJ/t liquid steel, with a similar order of magnitude. The technology might be attractive in terms of CO_2 emissions, and if the carbon content of electricity is sufficiently low. The most promising options for electrolysis are aqueous alkaline electrolysis, also called electrowinning, and iron ore pyroelectrolysis. Both technologies have already been shown possible at very small scale while commercial application may still be decades away. In the U.S., the Massachusetts Institute of Technology, AISI, and DOE jointly investigate the opportunities of electrolysis processes for ironmaking.

HIsarna is a technology based on bath-smelting. It combines coal preheating and partial pyrolysis in a reactor, a melting cyclone for ore melting and a smelter vessel for final ore reduction and iron production. It requires significantly less coal usage and thus reduces the amount of CO_2 emissions. Furthermore, it is a flexible process that allows partial substitution of coal by biomass, natural gas or even hydrogen. The HIsarna process is based on the Cyclone Converter Furnace developed by Hoogovens (The Netherlands). The Cyclone Converter Furnace technology incorporates the results of earlier AISI projects to develop convertor-based reduction processes. A pilot plant will be operational in early 2010. Additional work is continuing on using CCS and biomass technology in combination with HIsarna.

Carbon capture and storage involves separation and capture of CO_2 from the flue gas, pressurization of the captured CO_2, transportation of the CO_2 via pipeline, and finally injection and long-term geologic storage of the captured CO_2. Several different technologies, at varying stages of development, have the potential to separate and capture CO_2. Some have been demonstrated at the slip-stream or pilot-scale, while many others are still at the bench-top or laboratory stage of development. Specific techniques that pertain to the Iron and Steel industry are CCS paired with Top Gas Recycling of Blast Furnace Gas or Advanced Direct Reduction.

Current CCS opportunities typically are believed to have a substantial parasitic load requirement that they will place upon the system from which they are capturing the CO_2 for sequestration. As a result, CCS can lower the energy efficiency of the overall process by as much as 30 percent. This scenario creates higher operating costs and lower energy efficiency while attempting to sequester GHG emissions. (AISI, 2011)

In 2010, an Interagency Task Force on Carbon Capture and Storage was established to develop a comprehensive and coordinated Federal strategy to speed the commercial development and deployment of clean coal technologies. The Task Force was specifically charged with proposing a plan to overcome the barriers to the widespread, cost-effective deployment of CCS within 10 years, with a goal of bringing 5 to 10 commercial demonstration projects online by 2016. As part of its work, the Task Force prepared a report that summarizes the state of CCS and identified technical and non-technical barriers to implementation. The development status of CCS technologies is thoroughly discussed in the Task Force report. For additional information on the Task Force and its findings on CCS as a CO_2 control technology, go to: http://www.epa.gov/climatechange/policy/ccs_task_force.html.

The U.S. is on track to meet a goal to have as many as six large-scale carbon capture and storage demonstration projects in operation by 2016. Those projects include the FutureGen 2.0 project planned in Morgan County, Ill., as well as large-scale projects planned through the Clean Coal Power Initiative and industrial carbon capture and storage programs. Over the next several years, the development and construction of several large-scale, commercial-scale facilities will occur with some of the projects possibly in operation by 2014 or 2015. These projects utilize a portion of the $3.4 billion appropriated to DOE for CCS projects from the American Recovery and Reinvestment Act. (McDonnell, 2012)

A.2 Near-Term Technologies

Transformational Technologies and Processes

According to industry experts, the greatest potential for reducing the energy intensity of steelmaking lies with development of new transformational technologies and processes. Examples of such transformational R&D efforts (applicable both to Integrated and EAF steelmaking) include the following: (1) molten oxide electrolysis (under development at Massachusetts Institute of Technology); (2) ironmaking by flash smelting using hydrogen (under development at the University of Utah); and (3) the paired straight hearth (PSH) furnace (under development at McMaster University in Ontario, Canada). Many of the industry studies were funded wholly or in part by DOE. **Section A.3** provides more details on active and completed research projects conducted by DOE and DOE's partnerships. (AISI, 2011)

The following additional areas are considered important R&D opportunities for EAF steelmaking: improved processes for low-grade scrap recovery, and sensible heat recovery from slag, fumes, and off-gases (EPA, 2007a). Other R&D opportunities noted in the industry study (EPA, 2007a), include increasing the efficiency of melting processes (0.4 MMBtu/ton or 0.47 GJ/tonne), integration of refining functions and reductions of heat losses prior to casting (0.35 MMBtu/ton or 0.41 GJ/tonne), economical heat capture from EAF waste gas (0.26 MMBtu/ton or 0.30 GJ/tonne), purification and upgrading to scrap, and effective use of slag and dust. Casting and rolling opportunities (applicable both to Integrated and EAF steelmaking) include the reduction of heat losses from cast products prior to rolling and/or reheating (0.75 MMBtu/ton or 0.87 GJ/tonne) and thin-strip casting (0.5 to 0.7 MMBtu/ton [0.3 to 0.8 GJ/tonne]). (EPA, 2007a)

Essar's Integrated DRI/EAF Steelmaking

The Essar Group, which acquired Minnesota Steel in late 2007, was constructing a $1.6-billion steel-making facility on the Mesabi iron ore range in Minnesota that would be the first of its type (from iron ore to steel product at the mine site) (Essar Steel Minnesota LLC, 2010). However, construction has been halted due to economic reasons. This new plant will produce 4.1 million tpy (3.7 million tonnes/yr) of direct reduced iron (DRI) pellets, most of which will be processed in EAF to produce 2.8 million tpy (2.5 million tones/yr) of steel slabs.

The DRI/EAF Integrated steel-making route requires less energy and produces lower emissions than traditional Integrated iron and steelmaking (i.e., coke battery, blast furnace, BOF). A DOE (2008) report claims the following reduction in emissions relative to traditional steelmaking:

Pollutant	Percent Reduction
CO	96
Volatile organic compounds	87
Sulfur dioxide	78
NO_x	65
Mercury	58
CO_2	41

Nucor's DRI Iron and Steel Production Facility

Nucor Corporation began construction of an iron and steel complex in St. James Parish, LA in early 2011. The Nucor facility will include a pig iron operation utilizing a DRI furnace. The entire complex will consist of the DRI furnace along with a pellet operation, blast furnace, coke ovens, and a steel mill. The entire complex represents a $3.4 billion investment, according to Nucor. (BNA, 2011) Upon start-up, this facility will be the first DRI facility in the U.S. Many DRI furnaces exist in various parts of the world, but especially the middle east, because of the abundant supply of natural gas that can be used to operate this type of process. A DRI is particularly suitable for developing countries where the amount of coking coal is limited. The PSD permit for this facility was the first to go through the BACT review process for GHG in the U.S. (in 1st quarter 2011).

EAF Steelmaking at an Integrated Plant

A facility owned by Wheeling-Pittsburgh Steel installed a state-of-the art EAF in December 2004 to replace its BOF for steelmaking. This was the first application of an EAF at an Integrated steel mill to convert molten iron from the blast furnace into steel. The EAF is continuously charged with molten iron and scrap (BOF and most EAF are batch processes), can use up to 100 percent scrap, recovers heat from the EAF exhaust to preheat the scrap, and produces 330 tons/hr (300 tonnes/hr) of steel. After the EAF was installed, one of the two blast furnaces was shut down. The company claimed there were significant cost and environmental benefits from the conversion. (Tenova, 2010) The facility is now owned by RG Steel, Inc.

Other Innovative Technologies

Endless Strip Production. This process is a new development in thin slab casting and direct rolling. Installation of this technology was started in 2008 at a plant in Cremona, Italy. The specific energy consumption should be 40 percent lower than that needed for a traditional rolling mill. For thin gauges, the suppression of the cold rolling and annealing cycle will allow energy savings of 60 percent with regard to the traditional cycle. Processing costs are characterized by lower energy consumption, lower costs for consumables (e.g., mould, rolling cylinders) and improved liquid steel yield (up to 98 percent). (Worrell, 1999)

Carbon-free fuel. Traditionally, carbon from fossil fuels is used in the steel industry to provide the chemical function of reducing oxide ores. This function could also be performed hydrogen or carbon-free electricity, since hydrogen reduction of iron ore has steam as a gas product instead of CO_2, or wood. Limitations of this approach are not technical, since the technologies in the area of pre-reduction are very mature; but are related to the political issue of resource depletion in the longer term. Research projects are underway, some in other countries along with U.S.

- Use of hydrogen-bearing materials in blast furnaces such as steam, natural gas and waste plastics to substitute coke and coal.
- Hydrogen produced from natural gas or by electrolysis of seawater.
- Use of wood to make iron in a charcoal blast furnace (used in Brazil).
- Hydrogen Flash Smelting (currently being investigated in U.S. by AISI, DOE, and University of Utah)

A.3 Energy Improvement Technologies from U.S. Department of Energy (DOE) and DOE Partnerships

The following are research and development projects performed by DOE. The first set of projects are currently underway to improve the energy efficiency, environmental performance, and productivity of the steel industry and include emerging technologies which are defined as technologies that are likely to be commercially available in the next 2 years. (DOE, 2009a) Also in this section are DOE energy efficiency success stories and also a description of completed DOE energy projects.

Emerging Technology - Advanced Process Development

- **Minimization of Blast Furnace Fuel Rate by Optimizing Burden and Gas Distributions**
  - Partners: Purdue University Calumet, AISI, Mittal Steel, Dofasco, and Severstal.
  - Summary: A computational fluid dynamics (CFD) model will help to optimize and burden distributions that can minimize fuel rate, thereby maximizing blast furnace energy efficiency and minimizing emissions.
  - Benefits: Increase pulverized coal injection rate and fuel efficiency, reduces carbon emissions, and optimizes blast furnace efficiency.
  - Status (August 2007): The project team has conducted an initial market study and developed a marketing plan. There are 28 blast furnaces currently operating in the U.S., of which, 13 are operated by this project's industrial partners. The newly developed CFD technology will be implemented in each industrial partner's blast furnace during the project period. Within 5 years of successful project completion, the remaining blast furnaces in the U.S. will be targeted for implementation. A final marketing and technology transfer plan will be developed as part of the final deliverables of this project.

- **Research, Development, and Field Testing of Thermochemical Recuperation for High-Temperature Furnaces**
  - Status: The contract ($4.5 million) was awarded in September 2008. AISI is leading a team with the Gas Technology Institute, Thermal Transfer Corporation, U.S. Steel, ArcelorMittal, Republic Engineered Products, the Steel Manufacturing Association, and the Ohio Department of Development to develop and test thermochemical recuperation for steel reheating furnaces to increase waste heat recovery that reduces energy consumption and costs. A thermochemical recuperator uses the partial-oxidation-of-fuel principle to recover energy from flue gases of heating processes.

Emerging Technology - Cokeless Ironmaking

- **Next Generation Metallic Iron Nodule Technology in Electric Furnace Steelmaking**
  - Partners: University of Minnesota-Duluth and Nu-Iron Technologies, LLC.
  - Benefits: Metallic iron nodule technology produces a high -quality scrap substitute, reduces production costs, increases steel quality produced by EAF, and enables more effective use of sub-bituminous coal. Successful development of this new ironmaking process will produce potentially lower cost steel scrap substitutes. In addition, greater availability of high-quality iron nodules will increase the quality of steel and the competitiveness of mini-mills and other steel producers.
  - Status (September 2007): Phase 1 is complete. The testing phase will involve quantifying overall energy use characteristics, types of material that can be processed, fuels needed for successful operation, and the overall economics predicted for full-scale implementation. Upon successful demonstration, the project team will begin plans to transition the technology for industrial use. Iron nodule technology could potentially use up to 30 percent less energy than utilizing rotary hearth furnace technology.

- **Paired Straight Hearth Furnace**
  - Status: The Phase 1 report (feasibility study) was completed in February 2006. The Bricmont, Inc., report and the McMaster University analysis concluded that it is feasible with current technology and construction practices to design, build, and operate a demonstration plant of the PSH furnace with a capacity of 46,000 ton per year (42,000 tonne per year) of DRI for an estimated cost of $16,729,000. A DOE contract ($1.5 million) was awarded in September 2008. AISI, in partnership with McMaster University, U.S. Steel, Bricmont, and Harper International, will work to optimize the PSH furnace technology and establish its scalability potential from the bench-scale stage. The PSH furnace is an alternative to the energy and carbon-intensive blast furnace commonly used to make steel. The technology has a lower coal rate in comparison with other alternative ironmaking processes because of thermodynamic and kinetic advantages.

Emerging Technology - Next Generation Steelmaking

- **Development of Next Generation Heating System for Scale-Free Steel Reheating, Phase 2**
  - Partners: E3M, Inc.; ACL-NWO, Inc.; Bloom Engineering Corp.; Steel Dynamics, Inc.; Air Products & Chemical; the Steel Manufacturers Association; and the Forging Industry Association.
  - Benefits: Scale-free reheating improves productivity by reducing downtime and labor to collect and remove scale. Scale-free reheating increases energy and cost efficiency of steel reheating, and reduces the amount of energy needed to replenish steel lost as oxides. By reducing the amount of steel lost to scale formation, this system improves the surface quality of the steel.
  - Status (September 2007): Completed Phase 1, which included three activities: (1) conducting a literature search and analyzed the options needed to create a process atmosphere required for scale-free reheating, (2) defining furnace operating parameters required to generate scale-free heating process atmosphere, and (3) conducting economic and technical analyses. Phase 2 will include conducting pilot-scale furnace heating tests on scale-free heating, defining heating system conditions, designing and validating a scale-free heating system for typical applications, and conducting energy, economic, and environmental analyses and modeling. During the commercialization phase, the scale-free heating burner will be tested for functionality in furnaces used for both conventional heating and scale-free heating.

DOE Success Stories (DOE, 2009d)

Collaborative R&D projects under the auspices of the Steel Industry of the Future have produced energy, environmental, and economical benefits for the industry and the nation. The following list contains examples of projects that have been commercially successful and demonstrated full-scale or completed industrial trials:

- Enhanced Spheroidized Annealing
- Mesabi Nugget Ironmaking Technology for the Future: High Quality Iron Nuggets Using a Rotary Hearth Furnace
- Dilute Oxygen Combustion
- Hot-Blast Stove Process Model
- Microstructure Engineering in Hot Strip Mills
- Nickel Aluminide Transfer Rolls
- NO_x Emission Reduction by Oscillating Combustion
  Development of a Process to Continuously Melt, Refine, and Cast High-Quality Steel.

Completed DOE Research and Development Projects (DOE, 2009c)

The following projects were recently completed. In some cases, the R&D produced a new technology that is now emerging in the marketplace. In other cases, the R&D results will help to guide future development of energy-efficient technologies and processes for the steel industry.

- Advanced Control in Blast Furnace
- Aluminum Bronze Alloys to Improve the System Life of Basic Oxygen and EAF Hoods, Roofs, and Side Vents
- Appropriate Resistance Spot Welding Practice for Advanced High-Strength Steels
- Automated Steel Cleanliness Analysis Tool
- CFD Modeling for High-Rate Pulverized Coal Injection in the Blast Furnace
- Characterization of Fatigue and Crash Performance of a New Generation of High Strength Steel
- Clean Steels: Advancing the State of the Art
- Cold Work Embrittlement of Interstitial-Free Steels
- Constitutive Behavior of High-Strength Multiphase Sheet Steels Under High-Strain Rate Deformation Conditions
- Controlled Thermal-Mechanical Processing of Tubes and Pipes
- Dephosphorization When Using DRI or Hot Briquetted Iron
- Development and Application of Steel Foam and Structures
- Development of a Process to Continuously Melt, Refine, and Cast High-Quality Steel
- Development of Next Generation Heating System for Scale-Free Steel Reheating, Phase 1
- Development of Oxygen-Enriched Furnace
- Elimination or Minimization of Oscillation Marks—A Path to Improved Cast Surface Quality
- Enhanced Inclusion Removal from Steel in the Tundish
- Enrichment of By-Product Materials from Steel Pickling Acid Regeneration Plants
- Feasibility Study for Recycling Use Automotive Oil Filters in a Blast Furnace (Final Report)
- Formability Characterization of a New Generation of High-Strength Steels
- Future Steelmaking Processes (December 2003)
- Geological Sequestration of Carbon Dioxide (CO_2) by Hydrous Carbonate Formation with Reclaimed Slag

- Hydrogen and Nitrogen Control in Ladle and Casting Operations
- Improved Criteria for Acceptable Yield Point Elongation of Surface Critical Steels
- Inclusion Optimization for Next-Generation Steel Products
- In Situ, Real-Time Measurement of Melt Constituents
- Integrating Steel Production with Mineral Sequestration
- Intelligent Inductive Processing
- Large-Scale Evaluation of Nickel Aluminide Rolls in a Heat-Treat Furnace
- Laser Contouring System
- Life Improvement of Pot Hardware
- Magnetic Gate System for Molten Metal Flow Control
- The Mesabi Nugget Research Project New Ironmaking Technology of the Future: High-Quality Iron Nuggets Using a Rotary Hearth Furnace
- Minimizing NO_x Emissions from By-Product Fuels in Steelmaking
- New Process for Hot-Metal Production at Low Fuel Rate—Phase 1 Feasibility Study
- New Ultra-Low–Carbon Steels with Improved Bake Hard Oak Ridge National Laboratory
- Novel Low-NO_x Burners for Boilers in the Steel Industry
- Optical Sensor for Post-Combustion Control in EAF Steelmaking
- Optimization of Post-combustion
- Plant Line Trial Evaluation of Viable Non-Chromium Passivation Systems for Electrolytic Tinplate
- Properties of Galvanized and Galvannealed Advanced High-Strength Hot-Rolled Steels
- Pulverized Coal Injection
- Quantifying the Thermal Behavior of Slags
- Real-Time Melt Temperature Measurement in a Vacuum Degasser Using Optical Optometry
- Recycling of Waste Oxides
- Removal of Residual Elements in the Steel Ladle
- Standard Methodology for the Quantitative Measurement of Steel Phase Transformation Kinetics
- Strip Casting: Anticipating New Routes to Steel Sheet
- Study of Deformation Behavior of Lightweight Steel Structures
- Submerged Entry Nozzles that Resist Clogging
- Suspension Hydrogen Reduction of Iron Oxide Concentrate
- Sustainable Steelmaking Using Biomass and Waste Oxides
- Technical Feasibility Study of Steelmaking by Molten Oxide Electrolysis
- Temperature Measurement of Galvanneal Steel
- Validation of the Hot Strip Mill Model
- Verification of Steelmaking Slag Iron Content

Appendix B. The U.S. Steel Industry

This section lists current Coke, Integrated Iron and Steel, and EAF plant locations. Also included here is historical energy intensity, current power generation by Iron and Steel facilities, and the use of slim slab casting, an energy-saving measure.

B.1 Plants and Locations

Tables B-1, B-2, and B-3 list the operating plants (in 2011) for the 19 Coke plants, 17 Integrated Iron and Steel plants, and 87 EAF plants, respectively, in the Iron and Steel sector. Several Integrated Iron and Steel plants are clustered around the Great Lakes, which facilitates the delivery of taconite (processed iron ore) by waterway from iron ore mines on the Mesabi iron ore range in Minnesota and Michigan. Most Coke plants are located at or near the Integrated Iron and Steel plants. Several Integrated Iron and Steel plants are in non-attainment areas for particulate matter with a diameter less than 2.5 micrometers ($PM_{2.5}$).

Table B-1. List of Coke Plants by City and State (ACCCI/AIST, 2011; AIST, 2011; EPA, 2001a)

No.	City	State	No. of Batteries	Coke Capacity (tpy)	Type of Plant	Type of Coke	Type of Battery	Cogeneration
1	Birmingham	AL	3	451,948	Merchant	Both	By-product	No
2	Tarrant	AL	3	699,967	Merchant	Foundry	By-product	Yes
3	Granite City-1	IL	3	650,000	Merchant	Furnace	Nonrecovery	Yes[b]
4	Granite City-2[a]	IL	2	584,000	Captive	Furnace	By-product	No
5	Burns Harbor[a]	IN	2	1,877,000	Captive	Furnace	By-product	No
6	East Chicago	IN	4	1,300,000	Merchant	Furnace	Nonrecovery	Yes[b]
7	Gary[a]	IN	3	2,249,860	Captive	Furnace	By-product	No
8	River Rouge	MI	1	1,050,000	Merchant	Furnace	By-product	No
9	Tonawanda	NY	1	268,964	Merchant	Foundry	By-product	No
10	Haverhill	OH	4	1,100,000	Merchant	Furnace	Nonrecovery	Yes[b]
11	Middletown-1[a]	OH	1	456,000	Captive	Furnace	By-product	No
12	Middletown-2	OH	6	550,000	Merchant	Furnace	Nonrecovery	Yes[b]
13	Warren	OH	1	549,000	Merchant	Furnace	By-product	No
14	Clairton	PA	12	5,573,185	Captive[c]	Furnace	By-product	Yes[d]
15	Erie	PA	2	214,951	Merchant	Foundry	By-product	No
16	Monessen	PA	2	372,581	Captive[c]	Furnace	By-product	No
17	Neville Island	PA	1	514,779	Merchant	Furnace	By-product	No
18	Vansant	VA	6	745,000	Merchant	Furnace	Nonrecovery[b]	No
19	Follansbee	WV	4	1,346,000	Merchant	Furnace	By-product	No
	Total Coke		**61**	**20,553,235**				

[a] Located at an Integrated Iron and Steel plant (see **Table B-2**).
[b] Includes recovery of waste heat from the battery stack.
[c] Sells its coke to parent company that is at another location.
[d] Combustion of excess COG.

Table B-2. List of Integrated Iron and Steel Plants by City and State (AIST, 2011; EPA, 2001b)

No.	City	State	No. of BOF	Steelmaking Capacity (tpy)	No. of Blast Furnace	Iron Capacity (tpy)	No. of Coke Batteries	Coke Capacity (tpy)	Sinter Capacity (tpy)
1	Fairfield	AL	3	2,920,000	1	2,190,000			
2	Granite City	IL	2	3,000,000	2	2,400,000	2	584,000	
3	Riverdale	IL	2	1,100,000					
4	Burns Harbor	IN	3	5,600,000	2	5,460,000	2	1,877,000	2,800,000
5	East Chicago (1)	IN	2	3,800,000	2	3,100,000			1,200,000
6	East Chicago (2)	IN	4	6,250,000	3	6,500,000			1,100,000
7	Gary	IN	6	8,730,000	4	7,340,000	3	2,249,860	4,400,000
8	Sparrows Point	MD	2	3,375,000	1	3,100,000			3,430,000
9	Dearborn	MI	2	4,100,000	1	2,190,000			
10	Ecorse	MI	2	3,900,000	3	4,150,000			
11	Cleveland	OH	4	5,100,000	2	3,100,000			
12	Lorain	OH	2	2,700,000	1	1,460,000			
13	Middletown	OH	2	2,640,000	1	2,300,000	1	456,000	
14	Mingo Junction	OH	*	2,400,000	1	1,350,000			
15	Warren	OH	2	2,040,000	1	1,460,000			
16	Braddock	PA	2	2,957,000	2	2,300,000			
17	Weirton	WV	2	3,000,000	2	2,700,000			
	Total Integrated		**44**	**64,112,000**	**30**	**51,100,000**	**8**	**5,166,860**	**12,930,000**

*The BOF has been replaced by an EAF.

Table B-3. List of EAF Steel Plants by City and State (AIST, 2009)

No.	City	State	Steel Type	No. of EAF	Capacity (tpy)
1	Axis	AL	C	1	1,250,000
2	Birmingham (1)	AL	C, S	1	800,000
3	Birmingham (2)	AL	C	1	600,000
4	Trinity	AL	C	2	2,400,000
5	Tuscaloosa	AL	C	1	1,300,000
6	Blytheville (1)	AR	C	2	3,000,000
7	Blytheville (2)	AR	C, H, S	2	2,750,000
8	Fort Smith	AR	C	2	500,000
9	Magnolia (Newport)	AR	C	1	300,000
10	Newport	AR	C	1	130,000
11	Mesa	AZ	C	1	280,000
12	Rancho Cucamonga	CA	C	1	750,000
13	Pueblo	CO	C	1	1,200,000
14	Claymont	DE	C	1	490,000
15	Baldwin	FL	C	1	1,100,000
16	Cartersville	GA	C	1	850,000
17	Muscatine	IA	C, H	1	1,250,000
18	Wilton	IA	C	1	450,000
19	Alton	IL	C	1	700,000
20	Bourbonnais	IL	C	1	850,000
21	Chicago	IL	C	2	90,000
22	Peoria	IL	C	1	999,800
23	Sterling	IL	C	1	1,100,000
24	Butler	IN	C	2	3,000,000
25	Columbia City	IN	C, H	2	2,000,000
26	Crawfordsville	IN	C, H	2	2,400,000
27	East Chicago	IN	C	1	500,000
28	Pittsboro	IN	C, H	1	720,000
29	Portage	IN	C	1	749,600
30	Ashland	KY	C	2	340,000
31	Ghent	KY	S	2	1,600,000
32	Warsaw	KY	C	2	1,600,000
33	LaPlace	LA	C	2	800,000
34	Jackson	MI	C	2	290,000
35	Monroe	MI	C	1	500,000
36	St. Paul	MN	C, H	1	600,000
37	Columbus	MS	C	1	1,700,000
38	Flowood	MS	C	1	550,000
39	Charlotte	NC	C	1	450,000
40	Cofield	NC	C	1	1,400,000
41	Norfolk	NE	C	1	1,100,000
42	Sayreville	NJ	C	1	750,000
43	Auburn	NY	C	1	630,000
44	Solvay	NY	H, S	1	50,000
45	Canton (1)	OH	C	1	1,650,000
46	Canton (2)	OH	H	1	889,600
47	Canton (3)	OH	H	2	1,000,000
48	Cleveland (Cuyahoga)	OH	C	1	700,000
49	Delta	OH	C	1	1,800,000
50	Mansfield	OH	S	2	952,650
51	Marion	OH	C	1	450,000
52	Steubenville (Mingo)	OH	C	1	2,400,000
53	Warren	OH	C	1	400,000
54	Youngstown	OH	C, H	1	650,300
55	Sand Springs	OK	C	2	600,000

(continued)

No.	City	State	Steel Type	No. of EAF	Capacity (tpy)
56	McMinnville	OR	C	1	830,000
57	Brackenridge	PA	H, S	2	550,000
58	Bridgeville	PA	H, S	1	150,000
59	Butler	PA	C, S	3	1,000,000
60	Coatesville	PA	C, H, S	1	880,000
61	Koppel	PA	C	1	450,000
62	Latrobe (1)	PA	H, S	1	60,000
63	Latrobe (2)	PA	C, H	2	60,000
64	Midland	PA	S	2	600,000
65	Oil City	PA	H, S	1	60,000
66	Reading	PA	H, S	6	140,000
67	Steelton	PA	C	1	1,200,000
68	Cayce-W. Columbia	SC	C	1	800,050
69	Darlington	SC	C, H	1	1,050,000
70	Georgetown	SC	C	1	550,000
71	Huger	SC	C	2	3,450,000
72	Gallatin	TN	C	1	500,000
73	Jackson	TN	C	1	710,000
74	Knoxville	TN	C	1	600,000
75	Memphis	TN	C	1	850,000
76	Jewett	TX	C	1	1,250,000
77	Longview	TX	C, H	2	125,000
78	Midlothian	TX	C, H, S	2	1,750,000
79	Seguin	TX	C	1	1,000,000
80	Vidor (Beaumont)	TX	C	1	670,000
81	Vinton (El Paso)	TX	C	2	250,000
82	Plymouth	UT	C	2	1,120,000
83	Petersburg	VA	C, H, S	1	1,200,000
84	Roanoke	VA	C	1	650,000
85	Seattle	WA	C	1	1,100,000
86	Saukville	WI	C	1	625,000
87	Huntington	WV	C	2	280,000
	Total EAF			**119**	**81,072,800**

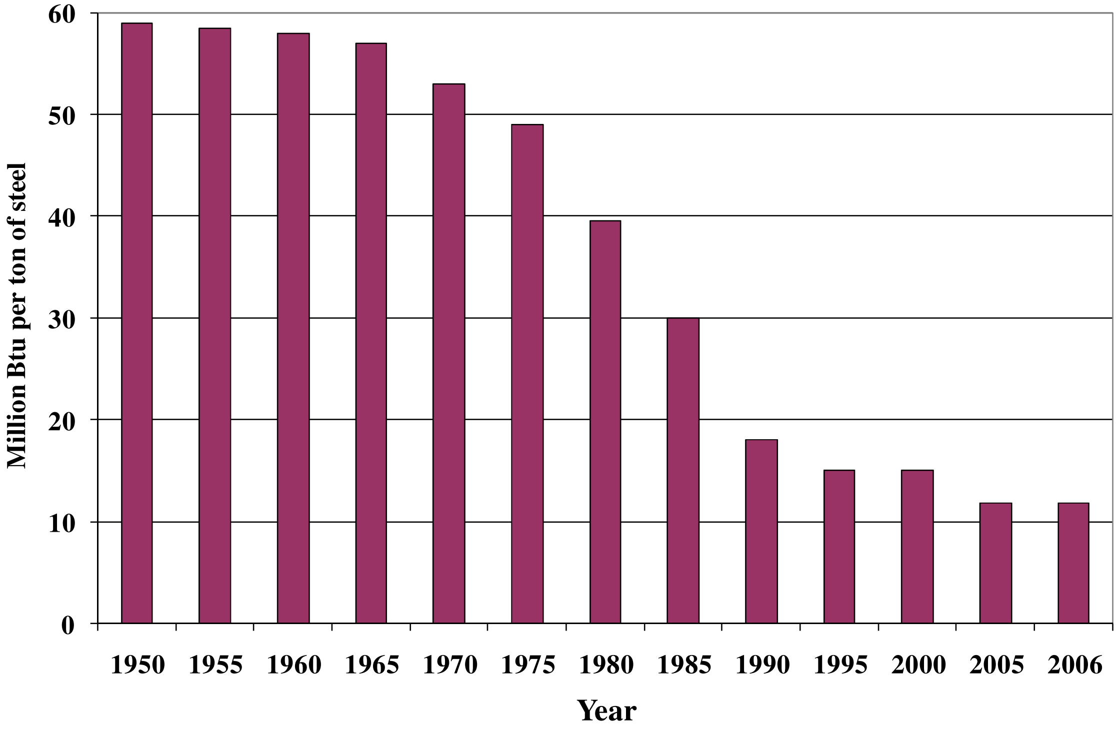
Note: C = carbon, H = high alloy, S = stainless, tpy = tons per year.

B.2 Energy Intensity

Current energy consumption in the Iron and Steel industry is estimated by DOE to be approximately 19 million British thermal units per ton of steel (MMBtu/ton) (22.1 GJ/tonne) for Integrated steel mills, 5.0 MMBtu/ton (5.8 GJ/tonne) for EAF (DOE, 2005); and 3.4 MMBtu/ton of coke (2.9 GJ/tonne). (DOE, 2000) As shown in **Figure B-1**, the U.S. Iron and Steel industry has reduced overall energy intensity for steel production dramatically since the 1950s. (AISI, 2011) A large part of this decrease is due to the increasing proportion of steel recycled in EAF since the 1970s; the energy intensity of secondary steelmaking is much less than the Integrated Iron and Steel process [19 MMBtu/ton vs. 5.0 MMBtu/ton (22 GJ/tonne] vs. 6 GJ/tonne)]. Some of the other contributors to the reduction include the widespread adoption of continuous casting, blast furnace coal injection, optimization of blast furnace operations, thin-slab casting, and the use of previously wasted process gases (BFG and COG) in furnaces and boilers.

As shown in **Table B-4**, several plants have installed cogeneration systems (EIA/DOE, 2003). The three newest Coke plants all recover the heat from the battery stack to produce steam and/or electricity. Integrated Iron and Steel plants use excess process fuel gases (BFG and COG) for cogeneration units.

Many plants have implemented thin-slab casting (see **Table B-5**), where thin slabs are slabs that are 2- to 4-in (5- to 10-cm) thick. This technology may be a future opportunity for a few more plants that produce thin slabs of steel. Thin-slab casting integrates casting and hot rolling into one process, which is estimated to reduce energy consumption by 4.2 MMBtu/ton (4.9 GJ/tonne) of crude steel. Between1994 and 2000, nine out of 16 slab castings units built were thin slab.



Source: American Iron and Steel Institute

Figure B-1. Historical energy consumption in the Iron and Steel industry.

Table B-4. Electricity Generation in the Iron and Steel Industry

Facility by Sector	Nameplate Capacity[a] (megawatts)
Coke Plants	
Erie, PA	2.5
Haverhill, OH[b]	46
Clairton, PA	81
East Chicago, IN[c]	94
Granite City, IL	139
Subtotal Coke	**363**
Steel Plants	
Warren, OH	21
Cleveland, OH	45
Fairfield, AL	82
East Chicago (1), IN	97
Sparrows Point, MD	170
Burns Harbor, IN	178
Gary, IN	231
East Chicago (2), IN	263
Subtotal Steel	**1,087**
Total Industry	**1,449**

[a] From EIA/DOE (2003) unless otherwise indicated.

[b] The Phase 1 coke batteries recovered the heat to produce steam for a nearby Sunoco chemical plant; the cogeneration unit was installed for the Phase 2 batteries to produce electricity for sale (from press releases).

[c] The cogeneration plant is owned by Primary Energy, a subsidiary of NIPSCO (from press releases).

Table B-5. U.S. Slab Casting Units Installed 1994–2000[a]

City	State	No. of Units	Year of Startup	Annual Capacity (1,000 tpy)	Median Product Thickness (in)	Thin Slab?
Hickman[b]	AR	1	1994	1,000	2.0	**Yes**
Crawfordsville[b]	IN	1	1994	1,000	2.0	**Yes**
Provo[c]	UT	1	1994	2,500	8.6	No
Ghent[b]	KY	1	1995	1,450	2.4	**Yes**
Mansfield[b]	OH	1	1995	750	4.0	**Yes**
Tuscaloosa	AL	1	1996	880	5.1	No
Butler-1[b]	IN	1	1996	2,400	2.2	**Yes**
Dearborn[c]	MI	1	1996	1,300	8.0	No
Delta	OH	1	1996	1,560	6.5	No
Muscatine	IA	1	1997	1,250	5.5	No
Portage[b]	IN	1	1997	700	3.5	**Yes**
Berkeley Cnty-1[b]	SC	1	1997	2,700	2.2	**Yes**
Butler-2[b]	IN	1	1998	2,400	2.2	**Yes**
East Chicago[c]	IN	1	2000	3,000	9.3	No
Sparrows Pt[c]	MD	1	2000	2,200	11	No
Berkeley Cnty-2[b]	SC	1	2000	2,700	2.2	**Yes**

[a] From 2003 Continuous Caster Roundup. (AIST, 2003)

[b] Uses thin-slab casting.

[c] Integrated iron and steel facility. The remaining facilities are EAF.

Appendix C - Detailed Estimates of Energy Costs and Savings

This appendix presents the results of research performed to investigate the costs of energy-saving measures used at facilities producing steel. Reductions in fuel consumption result in reductions of direct emissions of GHGs at the steel plant, and reductions in electricity usage result in reductions of indirect emissions (i.e., emissions from the power plant supplying the electricity). The costs in **Tables C-1** and **C-2** were taken from Worrell (1999, 2009). The Worrell costs were adjusted from 1994 to 2008 dollars using the Chemical Engineering Plant Cost Index.[8] In addition, costs and energy savings are presented as "per tonne"[9] of product from the process (e.g., where "product" is steel from steelmaking furnaces, coke from Coke plants, and sinter from sinter plants). The annual operating costs in these tables do not include the energy savings from fuel or electricity. The value of the energy savings for fuel and electricity are very site-specific and depend upon many factors, such as the region of the country, special contract rates (e.g., based on quantity used, and for electricity, whether it is consumed during periods of peak demand), and changes in market price over time (e.g., fluctuations in the price of natural gas).

An industry trade association (AISI, 2011) provided comments on the technical feasibility and cost-effectiveness of each of the various energy options in **Tables C-1** and **C-2**. The industry comments indicate one or more of the following conditions for each option: (1) site-specific variables that might affect costs and/or practicality of using the option at all facilities; (2) could improve energy efficiency and potentially lower GHG emissions but may increase other pollutants; (3) already widely implemented at most existing facilities; (4) only feasible for new units; (5) immature technology and/or practice, because it is still being researched and/or is in the pilot stage, at least as applied to the Iron and Steel sector; and (6) specialized process only technically appropriate for some equipment configurations or types. It was noted that payback times of more than three years are not likely to be considered economically feasible by a facility. (AISI, 2011)

There are several important caveats associated with the information in the tables here that require caution in extrapolating to every Iron and Steel sector plant. Because many of the measures were based on the experience of a single plant or an individual application of the measure, or in some cases best estimates based on the available information, the actual feasibility could be quite different when applied to other plants because of the numerous site-specific differences among plants. In addition, many measures may not be applicable to certain plants because of process configurations, product type or quality constraints, or the fact that the measure or a similar one has already been applied. Some equipment modifications may incur significant retrofit costs that affect their ability to be implemented. The choice of which measures might be the most appropriate to implement at a given facility should be based on a detailed analysis to assess site-specific costs, savings, and potential GHG emission reductions.

The costs in the tables that follow, adjusted by the cost index, do not reflect changes in actual conditions such as the installation of new and possibly better equipment that may have reduced the need for additional energy-saving technology while producing similar reductions in GHG emissions. Although the options in the tables are good examples of the types of operational changes possible to reduce energy consumption, site-specific operations can vary significantly from plant to plant, so that in some cases the estimated cost savings may not be realized. Consequently, implementation of the technologies cited here may not actually achieve in reality as high a reduction in GHG emissions as cited in the case studies. (AISI, 2011)

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[8] The Chemical Engineering Plant Cost Index accounts for the changes in costs over time and is used to provide costs on a common year basis for comparisons. In this case, costs in 1994 dollars are multiplied by 1.56 to estimate the costs in 2008 dollars. The multiplier of 1.56 is the 2008 cost index (575.4) divided by the 1994 cost index (368.1).

[9] A metric tonne is a unit of mass equal to 1,000 kg (2,205 lb); conversely, 1 ton (2,000 lb) is equal to 0.907 metric tonnes, and used mostly in the U.S. The U.S. ton is sometimes called a "short" ton

Table C-1. Energy Efficiency Technologies and Measures Applied to Integrated Steel Production in the U.S. (Worrell 1999, 2009; AISI, 2011)

Option	Emission Reduction (kg of CO_2/ tonne of product)	Fuel Savings (GJ/tonne of product)	Electricity Savings (GJ/tonne of product)	Annual Operating Costs ($/tonne of product)[a]	Retrofit Capital Costs ($/tonne of product)[a]	Applicability and Feasibility Codes (see list of codes below)[b]	Payback Time[c] (years)
Iron Ore Preparation (Sintering)							
Sinter plant heat recovery	57.2	0.55	0.0	0.0	4.7	C	2.8
Emission optimized sintering							
Reduction of air leakage	2.0	0.0	0.0	0.0	0.14	C	1.3
Increasing bed depth	9.9	0.09	0.0	0.0	0.0	C, S	0.0
Improved process control	5.0	0.05	0.0	0.0	0.21	C, EX	1.4
Use of waste fuels (e.g., lubricants) in sintering	19.5	0.18	0.0	0.0	0.29	C, S	0.5
Improve charging method							
Improve ignition oven efficiency							
Cokemaking							
Coal moisture control	6.7	0.30	0.0	0.0	76.6	C, EX	> 50
Programmed heating	3.8	0.17	0.0	0.0	0.37	C, EX	0.7
Variable speed drive COG compressor	0.12	0.0	0.0	0.0	0.47	C	21.2
Coke dry quenching	27.5	1.2	0.0	0.78	109.5	C	35.7
Additional use of COG						C, EX	
Single chamber system						C, N	
Non-recovery coke ovens						C, EX	
Ironmaking - Blast Furnace							
Pulverized coal injection to 130 kg/ton iron	47.0	0.77	0.0	-3.1	11.0		2.0
Pulverized coal injection to 225 kg/ton iron	34.7	0.57	0.0	-1.6	8.1	C, N	2.4
Injection of natural gas to 140 kg/ton iron	54.9	0.90	0.0	-3.1	7.8	C, EX	1.3
Injection of oil						C	
Injection of COG and BOF gas						C	<1.0
Charging carbon composite agglomerates						P	
Top pressure recovery turbines (wet type)	17.6	0.0	0.11	0.0	31.3	C, N	29.8
Recovery of BFG	4.0	0.07	0.0	0.0	0.47	C, EX	2.3
Hot-blast stove automation	22.6	0.37	0.0	0.0	0.47	EX	0.4
Recuperator hot-blast stove	4.9	0.08	0.0	0.0	2.2	C	8.7
Improvement of combustion in hot stove						C, EX	

Option	Emission Reduction (kg of CO_2/ tonne of product)	Fuel Savings (GJ/tonne of product)	Electricity Savings (GJ/tonne of product)	Annual Operating Costs ($/tonne of product)[a]	Retrofit Capital Costs ($/tonne of product)[a]	Applicability and Feasibility Codes (see list of codes below)[b]	Payback Time[c] (years)
Improved blast furnace control systems	24.4	0.40	0.0	0.0	0.56	EX	0.4
Blast furnace gas recycling						P	
Slag heat recovery						P	
Steelmaking - Basic Oxygen Furnace (BOF)							
BOF gas plus sensible heat recovery	46.0	0.92	0.0	0.0	34.4	C	11.9
Variable speed drive on ventilation fans	0.51	0.0	0.003	0.0	0.31	C, EX	9.9
Improvement of process monitoring/control						EX	
Programmed and efficient ladle heating						C, EX	
Casting							
Efficient caster ladle/tundish heating	1.1	0.02	0.0	0.0	0.09	C, EX	1.3
Near net shape casting - thin slab	728.8	3.5	0.64	-54.8	234.9	N, S	3.3
Near net shape casting – strip				25% less		N, S	
General Measures for Rolling Mills							
Energy efficient drives	1.6	0.0	0.01	0.0	0.30	EX	3.2
Gate communicated turn-off inverters							
Install lubrication system			0.016			EX	
Hot Rolling							
Proper reheating temperature							
Avoiding overload of reheat furnaces						EX	
Hot charging	30.2	0.60	0.0	-2.1	23.5	EX, N, S	5.9
Process control in hot strip mill	15.1	0.30	0.0	0.0	1.1	EX	1.2
Recuperative and regenerative burners	35.2	0.70	0.0	0.0	3.9	C, EX	1.8
Flameless burners	60%	60%				C	
Insulation of furnaces	8.0	0.16	0.0	0.0	15.6	C, EX	31.0
Walking beam furnace			25%			C, EX, N	
Controlling oxygen levels and/or speed on combustion air fans	16.6	0.33	0.0	0.0	0.79	C	0.8
Heat recovery to the product		50%		32%		C. N	
Waste heat recovery (cooling water)	1.9	0.03	0.0	0.11	1.3	C, P	> 50
Cold Rolling and Finishing							
Heat recovery on the annealing line	17.5	0.30	0.02	0.0	4.2	C, EX	4.0
Reduced steam use (pickling line)	9.9	0.19	0.0	0.0	4.4	C, EX	7.3
Automated monitoring and targeting system	35.3	0.0	0.21	0.0	1.7	C, EX	0.8

Option	Emission Reduction (kg of CO_2/ tonne of product)	Fuel Savings (GJ/tonne of product)	Electricity Savings (GJ/tonne of product)	Annual Operating Costs ($/tonne of product)[a]	Retrofit Capital Costs ($/tonne of product)[a]	Applicability and Feasibility Codes (see list of codes below)[b]	Payback Time[c] (years)
Inter-electrode insulation in electrolytic pickling line						P	
Continuous annealing						N	
General							
Preventive maintenance	35.7	0.43	0.02	0.03	0.02	EX	
Energy monitoring and management system	9.5	0.11	0.01	0.0	0.23	EX	0.5
Combined heat and power/cogeneration	82.1	0.03	0.35	0.0	22.7	EE, EX, N	6.1
High-efficiency motors							
Variable speed drives: flue gas control, pumps, and fans	1.5	0.0	0.02	0.0	2.0	C, EX	10.7

[a] These costs are those that were reported; actual costs will vary according to specific circumstances at a plant.

[b] Applicability codes (AISI, 2011):

C = Site-specific variables may affect costs and/or practicality of use at all facilities.
EE = Options that could improve energy efficiency and potentially GHG emissions but, may increase other criteria pollutant emissions if implemented.
EX = Process already widely implemented at many existing facilities.
N = Only feasible for new units..
P = Immature process that is still in research and/or pilot stage as applied to the Iron and Steel sector.
S = Specialized process only technically appropriate for some equipment configurations or types.

[c] Options with payback times of more than three years are not likely to be considered economically feasible by a facility. (AISI, 2011)

Table C-2. Energy Efficiency Technologies and Measures Applied to EAF Steel Production in the U.S. (Worrell 1999, 2009; AISI, 2011)

Option	Emissions Reduction (kg CO_2/tonne of product)	Fuel Savings (GJ/tonne of product)	Electricity Savings (GJ/tonne of product)	Annual Operating Costs ($/tonne of product)[a]	Retrofit Capital Costs ($/tonne of product)[a]	Applicability and Feasibility Codes (see list of codes below)[b]	Payback Time (years)[c]
Steelmaking - Electric Arc Furnace							
Improved process control (neural network)	17.6	0.0	0.11	-1.6	1.5	EX	0.5
Adjustable speed drives			0.05		2.0	EX	2–3
Transformer efficiency—ultra-high power transformers	10.0	0.0	0.06	0.0	4.3	C, EX	5.2
Bottom stirring/stirring gas injection	11.7	0.0	0.07	-3.1	0.94	C, EE, N	0.2
Foamy slag practice	10.6	0.0	0.07	-2.8	15.6	C, EX	4.2
Oxy-fuel burners	23.5	0.0	0.14	-6.2	7.5	C, EX	0.9
Post-combustion of the flue gases						C, EX,	
DC arc furnace	52.9	0.0	0.32	-3.9	6.1	C, N	
Scrap preheating—tunnel furnace (Consteel)	35.2	0.0	0.22	-3.0	7.8	C, EE, S	
Scrap preheating, post-combustion—shaft furnace (Fuchs)	35.3	-0.70	0.43	-6.2	9.4	C, EE, N, S	
Engineered refractories			0.036				
Airtight operation			0.36			P	
Contiarc furnace			0.72			C, N, S	
Flue gas monitoring and control	8.8	0.0	0.05	0.0	3.1	C, EX	4.3
Eccentric bottom tapping on existing furnace	8.8	0.0	0.05	0.0	5.0	C, N, S	6.8
DC twin-shell with scrap preheating	11.1	0.0	0.07	-1.7	9.4	C, EE, N	3.5
Casting							
Efficient caster ladle/tundish heating	1.1	0.02	0.0	0.0	0.09	EX	1.3
Near net shape casting - thin slab	265.3	3.2	0.64	-54.8	234.8	C, EX	3.3
Near net shape casting - strip				25% less		C	
Hot Rolling							
Proper reheating temperature						EX	
Avoiding overload of reheat furnaces						EX	
Energy efficient drives in the rolling mill	1.6	0.0	0.01	0.0	0.30	EX	5.9
Process control in hot strip mill	15.1	0.30	0.0	0.0	1.1	EX	1.2
Recuperative and regenerative burners	35.2	0.70	0.0	0.0	3.9	C, EX	1.8
Flameless burners	60%	60%				C, EX	
Insulation of furnaces	8.1	0.16	0.0	0.0	15.7	C, EX	31.0

Option	Emissions Reduction (kg CO_2/tonne of product)	Fuel Savings (GJ/tonne of product)	Electricity Savings (GJ/tonne of product)	Annual Operating Costs ($/tonne of product)[a]	Retrofit Capital Costs ($/tonne of product)[a]	Applicability and Feasibility Codes (see list of codes below)[b]	Payback Time (years)[c]
Walking beam furnace			25%			C, N	
Controlling oxygen levels and/or variable speed drives on combustion air fans	16.6	0.33	0.0	0.0	0.79	C, P	
Heat recovery to the product		50%		32%		C	
Waste heat recovery (cooling water)	1.9	0.03	0.0	0.11	1.3	C, P	> 50
General							
Preventive maintenance	15.0	0.09	0.05	0.03	0.02	EX	
Energy monitoring and management systems	3.7	0.02	0.01	0.0	0.23	EX	0.9

[a] These costs are those that were reported; actual costs will vary according to specific circumstances at a plant. See Table C- 1 for energy efficiency measures applicable to rolling and finishing operations

[b] Applicability codes (AISI, 2011):

C =	Site-specific variables may affect costs and/or practicality of use of the option at all facilities.
EE =	Options that could improve energy efficiency and potentially lower GHG emissions but may increase other pollutants.
EX =	Process already widely implemented at many existing facilities.
N =	Only feasible for new units.
P =	Immature process that is still in research and/or pilot stage as applied to the Iron and Steel sector.
S =	Specialized process only technically appropriate for some equipment configurations or types.

[c] Options with payback times of more than three years are not likely to be considered economically feasible by a facility. (AISI, 2011)

Appendix D. Processes and Emissions in the Iron and Steel Industry

D.1 Overview of Processes in the Iron and Steel Industry (EPA, 2001b; 2008b)

The Iron and Steel industry in the U.S. is the third largest in the world (after China and Japan), accounting for approximately 8 percent of the world's raw iron and steel production and supplying several industrial sectors, such as construction (building and bridge skeletons and supports), vehicle bodies, appliances, tools, and heavy equipment. The Iron and Steel industry actually includes three industries that have been traditionally treated as three different source categories: Coke Ovens, Integrated Iron and Steel, and EAF steel (secondary steelmaking that primarily recycles steel scrap).

D.1.1 Sinter Production

Sintering is a process that recovers the raw material value of many waste materials generated at Integrated Iron and Steel plants that would otherwise be landfilled or stockpiled. An important function of the sinter plant is to return waste iron-bearing materials to the blast furnace to produce iron. Another function is to provide part or all of the flux material (e.g., limestone, dolomite) for the ironmaking process. There are currently five facilities with sintering operations, and all of the sinter plants are part of Integrated Iron and Steel plants.

Sintering is a continuous process. Feed material to the sintering process includes ore fines, coke, reverts (including blast furnace dust, mill scale, and other by-products of steelmaking), recycled hot and cold fines from the sintering process, and trim materials (e.g., calcite fines, and other supplemental materials needed to produce a sinter product with prescribed chemistry and tonnage). The materials are proportioned and mixed to prepare a chemically uniform feed to the sinter strand, so that the sinter will have the qualities desired for satisfactory operation of the blast furnace. The chemical quality of the sinter is often assessed in terms of its basicity, which is the percent total basic oxides divided by the percent total acid oxides {[CaO + MgO (calcium oxide plus magnesium oxide)]])/[(SiO_2 + Al_2O_3) (silicon dioxide plus aluminum oxide)]}; sinter basicity is generally 1.0 to 3.0. The relative amounts of each material are determined based on the desired basicity, the rate of consumption of material at the sinter strand, the amount of sinter fines that must be recycled, and the total carbon content needed for proper ignition of the feed material.

The sintering machine accepts feed material and conveys it down the length of the moving strand. Near the feed end of the grate, the bed is ignited on the surface by gas burners and, as the mixture moves along on the traveling grate, air is pulled down through the mixture to burn the fuel by downdraft combustion; either COG or natural gas may be used for fuel to ignite the undersized coke or coal in the feed.

On the underside of the sinter strand is a series of windboxes that draw combusted air down through the material bed into a common duct, leading to a gas-cleaning device. The fused sinter is discharged at the end of the sinter strand, where it is crushed and screened. The sinter product is cooled in open air or in a circular cooler with water sprays or mechanical fans. The cooled sinter is crushed and screened a final time, and then is sent to be added or "charged" to the blast furnaces.

D.1.2 Blast Furnace Iron Production

Blast Furnace Operation

Iron is produced in blast furnaces by the reduction of iron-bearing materials with a hot gas. The large, refractory-lined furnace is charged through its top with iron ore pellets, sinter, flux (limestone and dolomite), and coke, which provides the fuel and forms a reducing atmosphere in the furnace. Many modern blast furnaces also inject pulverized coal or other sources of carbon to reduce the quantity of coke required. Iron oxides, coke, coal, and fluxes react with the heated blast air injected near the bottom of the furnace to form molten reduced iron, CO, and slag, which is a molten liquid solution of silicates and oxides that solidifies upon cooling. The molten iron and slag collect in the hearth at the base of the furnace. The by-product gas is collected at the top of the furnace and is recovered for use as fuel.

The production of 1 ton (0.91 tonne) of iron requires approximately 1.4 tons (1.3 tonnes) of ore or other iron-bearing material; 0.5 to 0.65 ton (0.45 to 0.59 tonne) of coke and coal; 0.25 ton (0.23 tonne) of limestone or dolomite; and 1.8 to 2 tons (1.6 to 1.8 tonnes) of air. By-products consist of 0.2 to 0.4 ton (0.18 to 0.36 tonne) of slag and 2.5 to 3.5 tons (2.3 to 3.2 tonnes) of BFG containing up to 0.05 tons (0.045 tonnes) of dust.

The molten iron and slag are removed (also called tapped), or cast, from the furnace in a semi-continuous process with 6 to 14 taps per day. The casting process begins by drilling a taphole into the clay-filled iron notch at the base of the hearth. During casting, molten iron flows into long troughs or “runners” that lead to transport containers, called “ladles.” Slag also flows from the furnace and is directed through separate runners to a slag pit adjacent to the casthouse or into slag pots for transport to a remote slag pit. At the end of tapping, the taphole is replugged with clay. The area around the base of the furnace, including all iron and slag runners, is enclosed by a casthouse. The molten iron is transferred to a refractory-lined rail car (also called a “torpedo” car because of it shape) and is then sent to the BOF shop. The hot metal is then poured from the torpedo cars into the BOF shop ladle; which is referred to as “hot-metal transfer” or “reladling.” Hot-metal transfer generally takes place under a hood to capture PM emissions, including kish (flakes of carbon), which is formed during the process.

Blast Furnace Gas

The BFG by-product, which is collected from the furnace top, has a low heating value and is composed of nitrogen (approximately 60 percent), CO (28 percent), and CO_2 (12 percent). Because of its high CO content, this BFG is used as a fuel within the steel plant. However, before BFG can be efficiently oxidized, the gas must be cleaned of dust or PM. Initially, the gases pass through a settling chamber or a dry cyclone to remove approximately 60 percent of the PM. Next, the gases undergo a one- or two-stage cleaning operation. The primary cleaner is normally a wet scrubber, which removes approximately 90 percent of the remaining PM. The secondary cleaner is a high-energy wet scrubber (usually a venturi) or an electrostatic precipitator, either of which can remove up to 90 percent of the PM that eludes the primary cleaner. Together, these control devices provide a clean gas of less than 0.02 grains per cubic foot (gr/ft^3) (0.05 grams per cubic meter [g/m^3]). A portion of this gas is fired in the blast furnace stoves that are used to preheat the air going into the blast furnace, and the remainder is used in other plant operations.

There are generally three to four stoves per blast furnace. Before the blast air is delivered to the blast furnace from the stoves, it is further preheated by passing it through a regenerator (heat exchanger) that uses some of the energy of the blast furnace off-gas that would otherwise have been lost. The additional thermal energy returned to the blast furnace (as heat) decreases the amount of fuel that has to be burned for each unit of hot metal and improves the efficiency of the process. In many furnaces, the off-gas is enriched by the addition of a fuel with much higher calorific value, such as natural gas or COG, to obtain even higher hot-blast temperatures. This decreases the fuel requirements and increases the hot-metal–production rate to a greater extent than is possible when burning BFG alone to heat the stoves.

Iron Preparation Hot-Metal Desulfurization

Sulfur in the molten iron is sometimes reduced before charging into the steelmaking furnace by adding reagents, such as soda ash, lime, and magnesium, in a process known as desulfurization. Injection of the reagents is accomplished pneumatically with either dry air or nitrogen. The reaction forms a floating slag, which can be skimmed off. Desulfurization may take place at various locations within a Iron and Steel facility; however, if the location is the BOF shop, then this process is most often accomplished at the hot-metal–transfer (reladling) station to take advantage of the fume collection system at that location.

D.1.3 Basic Oxygen Furnaces Steelmaking Process (EPA, 2001b; 2008b)

The BOF is a large, open-mouthed pear-shaped vessel lined with a basic refractory material that refines iron into steel. The term "basic" refers to the chemical characteristic or pH of the lining. The BOF receives a charge composed of molten iron from the blast furnace and ferrous scrap. The charge is typically 70 percent molten iron and 30 percent steel scrap. A jet of high-purity oxygen is injected into the BOF, which oxidizes the carbon and silicon in the molten iron to remove these constituents and to provide heat for melting the scrap. After the oxygen jet is started, lime is added to the top of the bath to provide a slag of the desired pH or basicity. Fluorspar (a mineral) and "mill scale" (an iron oxide waste material generated by rolling mills) are also added to achieve the desired slag fluidity. The oxygen combines with the unwanted elements (with the exception of sulfur) to form oxides, which leave the bath as gases or enter the slag. As refining continues and the carbon content decreases, the melting point of the bath increases. Sufficient heat must be generated from the oxidation reactions to keep the bath molten.

The distinct operations in the BOF process are the following:

- Charging—Adding molten iron and metal scrap to the furnace;
- Oxygen blow—Introducing oxygen into the furnace to refine the iron;
- Turndown—Tilting the vessel to obtain a sample and check temperature;
- Reblow—Introducing additional oxygen, if needed;
- Tapping—Pouring the molten steel into a ladle; and
- Deslagging—Pouring residual slag out of the vessel.

There are currently three methods that are used to supply the oxidizing gas: (1) top blown, (2) bottom blown, and (3) combination blowing. Most bottom-blown furnaces use tuyeres consisting of two concentric pipes, in which oxygen is blown through the center of the inner pipe and a hydrocarbon coolant (such as CH_4) is injected between the two pipes. The hydrocarbon decomposes at the temperature of liquid steel, absorbing heat as it exits and protecting the oxygen tuyere from overheating and burn back.

In the BOF process, molten iron from a blast furnace and iron scrap are refined in a furnace by lancing (or injecting) high-purity oxygen. In this thermochemical process, careful computations are made to determine the necessary percentage of molten iron, scrap, flux materials, and alloy additions. Various steel-making fluxes are added during the refining process to reduce the sulfur and phosphorus content of the metal to the prescribed level. The oxidation of silicon, carbon, manganese, phosphorus, and iron provide the energy required to melt the scrap, form the slag, and raise the temperature of the bath to the desired temperature. The oxygen reacts with carbon and other impurities to remove them from the metal. Because the reactions are exothermic, no external heat source is necessary to melt the scrap and to raise the temperature of the metal to the desired range for tapping. The large quantities of CO produced by the reactions in the BOF can be controlled by combustion at the mouth of the furnace and then vented to gas-cleaning devices, as with open hoods, or combustion can be suppressed at the furnace mouth, as with closed hoods. The full furnace cycle typically takes 25 to 45 minutes.

D.1.4 Electric Arc Furnace Steelmaking

Electric arc furnaces are used to produce carbon and alloy steels. These steel-making furnaces are operated as a batch process that includes charging scrap and other raw materials, melting, removing slag (“slagging”), and tapping. The length of the operating cycle is referred to as the tap-to-tap time, and each batch of steel produced is known as a “heat.” Tap-to-tap times range from 35 minutes to more than 200 minutes, with generally higher tap-to-tap times for stainless and specialty steel. Newer EAF are designed to achieve a tap-to-tap time of less than 60 minutes.

The input material to an EAF is typically scrap and iron units such as pig iron, DRI, and HBI. Cylindrical refractory-lined EAF are equipped with carbon electrodes to be raised or lowered through the furnace roof. With electrodes retracted, the furnace roof can be rotated aside to permit the charge of scrap steel by overhead crane. After ferrous scrap and other materials are charged to the EAF, the melting phase begins when electrical energy is supplied to the carbon electrodes. Electric current of the opposite polarity electrodes generates heat between the electrodes and through the scrap. Oxy-fuel burners and oxygen lances may also be used to supply chemical energy. Oxy-fuel burners, which burn natural gas and oxygen, use convection and flame radiation to transfer heat to the scrap metal. Oxygen lances are used to inject oxygen directly into the molten steel; exothermic reactions with the iron and other components provide additional energy to assist in melting the scrap and removing excess carbon. Alloying agents and fluxing materials usually are added through the doors on the side of the furnace to achieve the desired composition. The process of charging the EAF and repeating the melting phase may occur several times per “heat” depending on the particular EAF and the raw materials that it is recycling.

Refining of the molten steel can occur simultaneously with melting, especially in EAF operations where oxygen is introduced throughout the batch. During the refining process, substances that are incompatible with iron and steel are separated out by forming a layer of slag on top of the molten metal. After completion of the melting and refining steps, the slag door is opened, and the furnace is tipped backward so the slag pours out (“slagging”). The furnace is righted, and the tap hole is opened. The furnace is then tipped forward, and the steel is poured (“tapped”) into a ladle (a refractory-lined vessel designed to hold the molten steel) for transfer to the ladle metallurgy station. Bulk alloy additions are made during or after tapping based on the desired steel grade.

Some EAF plants, primarily the small specialty and stainless steel producers, use AOD to further refine the molten steel from the EAF to produce low-carbon steel. In the AOD vessel, argon and oxygen are blown into the bottom of the vessel, and the carbon and oxygen react to form CO_2 and CO, which are removed from the vessel.

D.1.5 Casting and Finishing

Casting

The steel produced by both BOF and EAF follow similar routes after the molten steel is poured from the furnace. The molten steel is transferred from ladle metallurgy to the continuous caster, which casts the steel into semi-finished shapes (e.g., slabs, blooms, billets, rounds, other special sections). Continuous casting is a relatively recent development, which has essentially replaced the ingot casting method because it increases the process yield from 80 percent to more than 95 percent and offers significant product quality benefits. Continuous casting has also decreased GHG emissions due to the increased yield and from a decrease in energy use as compared to energy-intensive ingot casting. Continuous casting is used to produce approximately 99 percent of the steel today. Both continuous and ingot casting are not estimated to be significant sources of GHGs.

Ingot casting was the common casting route prior to continuous casting, and only a small amount of steel is now processed using this route. In this process, molten steel is poured from the ladle into an ingot mold, where it cools and begins to solidify. The molds are stripped away, and the ingots are transported to a soaking pit or to a reheat furnace where they are heated to a uniform temperature. The ingots are shaped by rolling them into semi-finished products, usually slabs, blooms, or billets, or by forging. Ingot casting is typically used for small specialty batches and certain applications for producing steel plates.

Whichever production technique is used, the slabs, blooms, or billets undergo a surface preparation step, called "scarfing," which removes surface defects before shaping or rolling. Scarfing can be performed by a machine applying jets of oxygen to the surface of hot semi-finished steel or by hand (with torches) on cold or slightly heated semi-finished steel.

Rolling Mills

Steel from the continuous caster is processed in rolling mills to produce steel shapes that are classified according to general appearance, overall size, dimensional proportions, and intended use. Slabs are always oblong, usually 2- to 9-in thick and 24- to 60-in wide (5- to 23- centimeter [cm] thick and 61- to 152-cm wide). Blooms are square or slightly oblong and are mostly in the range of 6-by-6 in to 12-by-12 in (15-by-15 cm to 30-by-30 cm). Billets are mostly square and range from 2-by-2 in to 5-by-5 in (5-by-5 cm to 13-by-13 cm). Rolling mills are used to produce the final steel shapes that are sold by the steel mill. These shapes include coiled strips, rails, and other structural shapes, as well as sheets and bars. Because rolling mills consume electricity, they consequently contribute to indirect emissions of GHGs.

D.1.6 Other Steel Finishing Processes and Combustion Sources

The semi-finished products may be further processed by using many different steps, such as annealing, hot forming, cold rolling, pickling, galvanizing, coating, or painting. Some of these steps require additional heating or reheating. The additional heating or reheating is accomplished using furnaces usually fired with natural gas. The furnaces are custom designed for the type of steel, the dimensions of the semi-finished steel pieces, and the desired temperature.

There are many different types of combustion processes at both Integrated Iron and Steel and EAF steel facilities that are not directly related to the major production processes previously discussed. However, the EAF facilities burn natural gas almost exclusively, whereas Integrated steel facilities burn a combination of fuels, including natural gas, COG, and BFG. The combustion units at both types of facilities include boilers, process heaters, flares, dryout heaters, and several types of furnaces. For example, soaking pits and reheat furnaces are used to raise the temperature of the steel until it is sufficiently hot to be plastic enough for economical reduction by rolling or forging. Annealing furnaces are used to heat the steel to relieve cooling stresses induced by cold or hot working and to soften the steel to improve machinability and formability. Ladle reheating uses natural gas to keep the ladle hot while waiting for molten steel. Natural gas is the most commonly used fuel, in general, at both types of steel-making facilities, but COG and BFG (depending on availability) are also used in some of the combustion processes at Integrated steel plants. The CO_2 emissions from combustion sources in 2007 were estimated at approximately 21 million tons (19 million tonnes) for EAF steel plants and 19 million tons (17 million tonnes) for Integrated Iron and Steel plants.

D.1.7 Coke Production

Most coke is produced in by-product recovery coke oven batteries. However, of the 19 U.S. Coke plants shown in **Table B-1**, there are four non-recovery coke oven batteries, including the three newest Coke plants. All three of the newest non-recovery plants use waste heat from combustion to generate electricity. The recovery of waste heat to generate electricity reduces the amount of purchased electricity or reduces the need to purchase additional fuel to generate electricity onsite. Recovered heat that is supplied to the grid also reduces the amount of electricity that must be produced; if this power is generated from fossil-fuel combustion, then the recovered heat lowers the amount of CO_2 emissions generated from combustion.

By-product Recovery Coke Oven Batteries

Thermal distillation is used to remove volatile non-carbon elements from coal to produce coke in ovens grouped together in “batteries.” A by-product coke oven battery consists of 20 to 100 adjacent ovens with common side walls made of high-quality silica and other types of refractory brick. The wall separating adjacent ovens and each end wall consists of a series of heating flues. At any one time, half of the flues in a given wall will be burning gas in combustion flues, and the other half of the flues will be conveying waste heat from the combustion flues to a heat exchanger and then to the combustion stack. Every 20 to 30 minutes, the battery “reverses,” the former waste heat flues become combustion flues, and the former combustion flues become waste heat flues. Because the flame temperature is above the melting point of the brick, this reversal avoids melting the battery brickwork and provides more uniform heating of the coal mass. Process heat is obtained from the combustion of COG in the combustion flues, which is sometimes supplemented with BFG. The BFG is introduced from piping in the basement of the battery where the gas flow to each flue is metered and controlled. Waste gases from combustion, including GHGs, exit through the battery stack.

Each oven holds between 15 and 25 tons (14 and 23 tonnes) of coal. Offtake flues remove gases evolved from the destructive distillation process. The operation of each oven in the battery is cyclic, but the batteries usually contain a sufficiently large number of ovens so that the yield of by-products is essentially continuous. Coking continues for 15 to 18 hrs to produce blast furnace coke and 25 to 30 hrs to produce foundry coke. The coking time is determined by the coal mixture, the moisture content, the rate of underfiring, and the desired properties of the coke. Coking temperatures generally range from 1,700°F to 2,000°F (900°C to 1,100°C) and are kept on the higher side of the range to produce blast furnace coke.

The coke oven process begins with pulverized coal that is mixed and blended, with water and oil sometimes added to control the bulk density of the mixture. The prepared coal mixture is then transported to the coal storage bunkers on the coke oven battery. A specific volume of coal is discharged from the bunker into a larry car, which is a vehicle that moves along the top of the battery. When the larry car is positioned over an empty, hot oven, the lids on the charging ports are removed, and the coal is discharged from the hoppers of the larry car into the oven. To minimize the escape of gases from the oven during charging, steam aspiration is used to draw gases from the space above the charged coal into a collecting main duct. After charging, the aspiration is turned off, and the gases are directed through an offtake system into the gas-collecting main duct.

The maximum temperature attained at the center of the coke mass usually ranges from 2,000°F to 2,800°F (1,100ºC to 1,500ºC). At this temperature, almost all volatile matter from the coal mass volatilizes and leaves a high-quality metallurgical coke. Ambient air is prevented from leaking into the ovens by maintaining a slight positive back pressure of approximately 10 mm of water. The positive pressure causes some COG to leak out of the ovens. The gases and hydrocarbons, including GHGs, that evolve during thermal distillation in the coke oven are removed through the offtake gas system and are sent to the by-product plant for recovery.

Near the end of the coking cycle, each oven is disconnected, or "dampered off," from the main collection duct. Once an oven is dampered off, a standpipe in the oven that is capped during the cycle is opened to relieve pressure. Volatile gases exit through the open standpipe and are ignited if they fail to self-ignite. These gases are allowed to burn until the oven has been emptied of coke, or "pushed." At the end of the coking cycle, doors at both ends of the oven are removed, and the hot coke is pushed out of the coke side of the oven by a ram that is extended from a pusher machine. The coke is then pushed through a guide trough into a special rail car (called a quench car), which traverses the coke side of the battery. The quench car carries the coke to a quench tower where the hot coke is deluged with water. The quenched coke is discharged onto an inclined "coke wharf" to allow excess water to drain and cool the coke to a lower temperature. Gates along the lower edge of the wharf control the rate that the coke falls onto a conveyor belt that carries it to a crushing and screening system.

Gases that evolve during coking leave the coke oven through standpipes, pass into goosenecks (curved piping that connects each oven's standpipe to the main collecting duct), and travel through a damper valve to the gas collection main duct that directs the gases to the by-product plant. These gases account for 20 to 35 percent by weight of the initial coal charge and are composed of water vapor, tar, light oils, heavy hydrocarbons, and other chemical compounds.

At the by-product recovery plant, tar and tar derivatives, ammonia, and light oil are extracted from the raw COG. At most Coke plants, after tar, ammonia, and light oil are removed, the gas undergoes a final desulfurization process to remove hydrogen sulfide before being used as fuel. Approximately 35 to 40 percent of cleaned COG (after the removal of economically valuable by-products) is used to heat the coke ovens, and the remainder is used in other operations related to steel production, in boilers, or is flared. COG is composed of approximately 47 percent hydrogen, 32 percent CH_4, 6 percent CO, and 2 percent CO_2.

Non-recovery Coke Oven Batteries (with Heat Recovery)

As the name implies, the non-recovery cokemaking process does not recover the numerous chemical by-products which were discussed above under by-product recovery. All of the COG is burned, and instead of recovering the chemicals, this process is usually accompanied by heat recovery, and in many cases also the cogeneration of electricity. Nonrecovery ovens are of a horizontal design (as opposed to the vertical slot oven used in the by-product process) with a typical range of 30 to 60 ovens per battery. The oven is generally between 30- and 45-feet (ft.) (9 and 14-meters [m]) long and 6- to 12-ft. (1.8- to 3.7-m) wide. The internal oven chamber is usually semi-cylindrical, with the apex of the arch 5 to 12 ft. (1.5 to 3.7 m) above the oven floor. Each oven is equipped with two doors, one on each side of the horizontal oven, but there are no lids or offtakes as found on by-product ovens. The oven is charged through the oven doorway with a coal conveyor rather than from the top through charging ports as in a recovery plant.

After a non-recovery oven is charged with coal, carbonization begins as a result of the heat radiated from the oven bricks used with the previous charge. Combustion products and volatiles that evolve from the coal mass are burned in the chamber above the coal, in the gas pathway through the walls, and beneath the oven in combustion flues ("sole" flues). Each oven chamber has two to six "downcomers" ducts in each oven wall; the sole flue may be subdivided into separate flues that are supplied by these downcomers. The sole flue is designed to heat the bottom of the coal charge by conduction, and radiant and convective heat flow is produced above the coal charge.

Primary combustion air is introduced into the oven chamber above the coal (the "crown") through one of several dampered ports in the door. The dampers are adjusted to maintain the proper temperature in the oven crown. Outside air may also be introduced into the sole flues; however, additional air is usually required in the sole flue only for the first hour or two after charging. All of the non-recovery ovens are maintained under a negative pressure and do not leak under normal operating conditions, unlike the by-product ovens, which are maintained under a positive pressure. The combustion gases are removed from the ovens and directed to the stack through a waste heat tunnel located on top of the battery centerline and extends the length of the battery.

D.2 Greenhouse Gas Emissions from Steelmaking Processes

D.2.1 GHG Emissions from Sinter Plants

The primary GHG emissions point of interest for the sinter plant is the stack that discharges the windbox exhaust gases after gas cleaning. The CO_2 is formed from the fuel combustion (COG or natural gas) and from carbon in the feed materials, including coke fines and other carbonaceous materials. The GHG emissions from sinter plants may vary widely over time as a consequence of variations in the fuel inputs and other feedstock, especially in the types and quantities of iron-bearing materials that are recycled. Because both natural gas and COG contain methane (CH_4), when these gases are burned, a small amount of the unburned CH_4 is emitted with the exhaust gases. Consequently, sinter plants (and any other process that burns fuels that contain CH_4) also emit a small amount of CH_4.

Based on the Intergovernmental Panel on Climate Change (IPCC) emissions factor of 0.2 ton of CO_2/ton of sinter (0.2 tonne of CO_2/tonne of sinter) and the production of 14.7 million tons (13.3 million tonnes) of sinter in 2007, CO_2 emissions are estimated at 3.0 million tons (2.7 million tonnes) of CO_2/year. (IPCC, 2007)

D.2.2 GHG Emissions from Blast Furnaces

The vast majority of GHGs (CO_2) is emitted from the blast furnaces' stove stacks where the combustion gases from the stoves are discharged. A small amount of emissions may also occur from flares, leaks in the ductwork for conveying the gas, and from blast furnace emergency venting. Emissions of CO_2 are also generated from the combustion of natural gas using flame suppression to reduce emissions of PM. In flame suppression, a flame is maintained over the surface of the molten metal, for example, during tapping, to consume oxygen and inhibit the formation of metal oxides that become airborne. Emissions also occur from the combustion of BFG in flares (flaring).

The IPCC Guidelines provide an emissions factor of 260 tonnes of CO_2 per terajoule for the combustion of BFG. Based on the production of 39.8 million tons (36.1 million tonnes) of pig iron in 2007, CO_2 emissions from blast furnace stoves would be approximately 26 million tons (24 million tonnes) of CO_2/yr. (IPCC, 2007)

D.2.3 GHG Emissions from Basic Oxygen Furnaces

The major emission point for CO_2 from the BOF is the furnace exhaust gas that is discharged through a stack after gas cleaning. The carbon is removed as CO and CO_2 during the oxygen blow. Carbon may also be introduced to a much smaller extent from fluxing materials and other process additives that are charged to the furnace.

Using the default values in the IPCC Guidelines for iron (0.04) and steel (0.01) for the fraction of carbon gives an emission factor of 0.11 ton of CO_2/ton of steel (0.11 tonne of CO_2/tonne of steel) for carbon removed from the iron as CO_2. Applying the emission factor to the production of 44 million tons (40 million tonnes) of steel in BOF in 2007 yields an estimate of 4.9 million tons (4.4 million tonnes) of CO_2/yr. (IPCC, 2007)

D.2.4 GHG Emissions from Electric Arc Furnace

The CO_2 emissions are generated during the melting and refining process when carbon is removed from the charge material and carbon electrodes as CO and CO_2. These emissions are captured and sent to a baghouse for removal of PM before discharge into the atmosphere. The AOD vessels are small contributors to CO_2 emissions.

The CO_2 emissions estimate of 5.1 million tons (4.6 million tonnes) of CO_2 for EAF is based on the IPCC Guidelines emission factor of 0.08 ton of CO_2/ton of steel (0.08 tonne of CO_2/tonne of steel) and the production of 64 million tons (58 million tonnes) of steel in 2007. (IPCC, 2007)

D.2.5 GHG Emissions from Coke Plants (EPA, 2008a)

The primary emissions point of gases at Coke plants is the battery's combustion stack. Test data were obtained for 53 emissions tests (generally three runs per tests) for CO_2 emissions from the combustion stacks at by-product recovery Coke plants for development of an emissions factor for 2008 revision to EPA's Compilation of Emission Factors in AP-42. (EPA, 2008a) These tests averaged 0.21 ton of CO_2/ton of coke (0.21 tonne of CO_2/tonne of coke).

Test results for a non-recovery battery were also obtained and analyzed. The average of three runs at one Coke plant resulted in an emissions factor of 1.23 ton of CO_2/ton of coke (1.23 tonne of CO_2/tonne of coke), approximately six times higher than the factor for the combustion stack at by-product recovery batteries. The emissions factor for non-recovery combustion stacks is much higher because all of the COG and all of the by-products are burned. In comparison, organic liquids (e.g., tar, light oil) are recovered at by-product recovery Coke plants, and only approximately one-third of the gas is consumed in underfiring the ovens.

Emissions from coke combustion stacks based on the 2007 production rate are estimated at 3.3 million tons (3 million tonnes) of CO_2 from non-recovery battery stacks at three Coke plants and 3.1 million tons (2.8 million tonnes) of CO_2 from by-product recovery battery stacks at 15 Coke plants. Emissions from the combustion of COG in units other than the coke battery underfiring system are estimated at 0.35 ton of CO_2/ton of coke (0.35 tonne of CO_2/tonne of coke). For the production of 8.7 million tons (7.6 million tonnes) of coke in stand-alone by-product Coke plants (i.e., 9 by-product Coke plants not located at Integrated Iron and Steel facilities), emissions from other combustion units would be 3.0 million tons (2.7 million tonnes) of CO_2/yr.

A small amount of CO_2 is emitted from the pushing operation when the incandescent coke is pushed from the oven and transported to the quench tower where it is quenched with water. The AP-42 emission factors provide an emissions factor of 0.008 ton of CO2/ton of coal (0.008 tonne of CO2/tonne of coal), which is equivalent to 0.01 ton of CO2/ton of coke (0.01 tonne of CO2/tonne of coke) (EPA, 2008a). Using the 2007 production rate for coke 17.4 million tons (15.8 million tonnes), the emissions from pushing are estimated at 0.174 million tons (0.158 million tonnes) of CO_2/yr.

Fugitive emissions occur during the coking process from leaks of raw COG that contains CH_4. The leaks occur from doors, lids, offtakes, and collecting mains and are almost impossible to quantify because they change in location, frequency, and duration during the coking cycle, and they are not captured in a conveyance. However, the number, size, and frequency of these leaks have decreased significantly over the past 20 years as a result of stringent regulations, including national standards, consent decrees, and state regulations. Many by-product recovery Coke plants also have other combustion sources, primarily boilers and flares. These units use excess COG that is not used for underfiring the battery or shipped offsite for use as fuel in other processes. The IPCC Guidelines provide an emissions factor of 0.56 ton of CO_2/ton of coke (0.56 tonne of CO_2/tonne of coke), assuming all of the COG is burned. (IPCC, 2007)

Table D-4. Estimates of GHG Emissions in 2010 for Iron and Steel Sector Using Emission Factors (EPA 2008a; IPCC, 2007)

Type of Facility or Unit	Number of Facilities	2010 Estimated Emissions [a] (million tons of CO_2/year) [b]				
		Process Units	Miscellaneous Combustion Units	Indirect Emissions (Electricity)	Industry Total	Average per Plant
Coke						
By-product coke (standalone)	10	3.4	3.3		6.7	0.7
By-product coke (co-located)[c]	4	0.9			0.9	0.2
Nonrecovery coke	5	5.3			5.3	1.1
All Coke	**19**	**9.7**	**3.3**		**13.0**	**0.5**
EAF						
All EAF	**87**	**5.0**	**19**	**24**	**48**	**0.6**
Integrated Iron and Steel						
By-product coke (co-located)[c]	4	0.9			0.9	0.2
Blast furnace	16	25			25	1.5
BOF	16	4.4			4.4	0.3
Sinter plant	5	3.0			3.0	0.6
All Integrated Iron and Steel	**17**	**33**	**17.5**	**6.8**	**57**	**3.4**
Total Iron and Steel Sector						
All Iron and Steel Sector[b]	**120**	**93**	**40**	**31**	**117**	**1.0**

[a] On October 30, 2009, EPA published a final rule for the mandatory reporting of GHG emissions (74 FR 56260- 56519). This rule required reporting of GHG emissions from all sectors of the economy starting in 2010 for facilities with GHG emissions over 25,000 tons per year CO_2 equivalents. The final rule applied to direct GHG emitters, such as facilities in the Iron and Steel sector, among other types of sources of GHG. The rule did not require control of GHG, rather it only required that sources above the threshold levels monitor and report GHG emissions. See http://www.epa.gov/climatechange/emissions/ghgrulemaking.html for more information on this rule. (EPA/OAR, 2008b) Because the information obtained by EPA as a result of this rule is likely to be more accurate than the above GHG emissions obtained from the use of generalized emission factors for the Iron and Steel industry, the information shown above should only be taken as an estimate in the interim. Facility-specific emission data are also a better source of data.

[b] To determine values in tonnes, multiply the values in tons by 0.907.

[c] Note that "By-product Coke (co-located)" at Integrated Iron and Steel plants are listed twice in the table but only included once in the All Iron and Steel Sector total.