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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
AISI	American Iron and Steel Institute
AIST	Association for Iron & Steel Technology
Al ₂ O ₃	aluminum oxide
ANSI	American National Standards Institute
AOD	argon-oxygen decarburization
BACT	best available control technology
BFG	blast furnace gas
BOF	basic oxygen furnace
Btu	British thermal unit
CaO	calcium oxide
CCAP	Center for Clean Air Policy
cm	centimeter
CCS	carbon capture and sequestration
CDM	Clean Development Mechanism
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	U.S. Department of Energy
DRI	direct reduced iron
EAF	electric arc furnace
EMS	Energy Management Systems
EM Standards	Energy Management Standards
EPA	U.S. 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
lbs	pounds
m	meter(s)
m ³	cubic meter
MMBtu	million British thermal units
MIT	Massachusetts Institute of Technology
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 meters)
PSD	prevention of significant deterioration
PSH	paired straight hearth
R&D	research and development
scf	standard cubic feet
SiO ₂	silicon dioxide
SO _x	sulfur oxide
tonne	metric ton
tpy	tons per year
UHP	ultra-high power
ULCOS	ultra-low CO ₂ steelmaking
VSD	variable-speed drive
yr	year

I. Introduction

This document is one of several white papers 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 in order 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 (CO₂), 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 manufacturing 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 U.S. 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.

Description of the Iron and Steel Industry

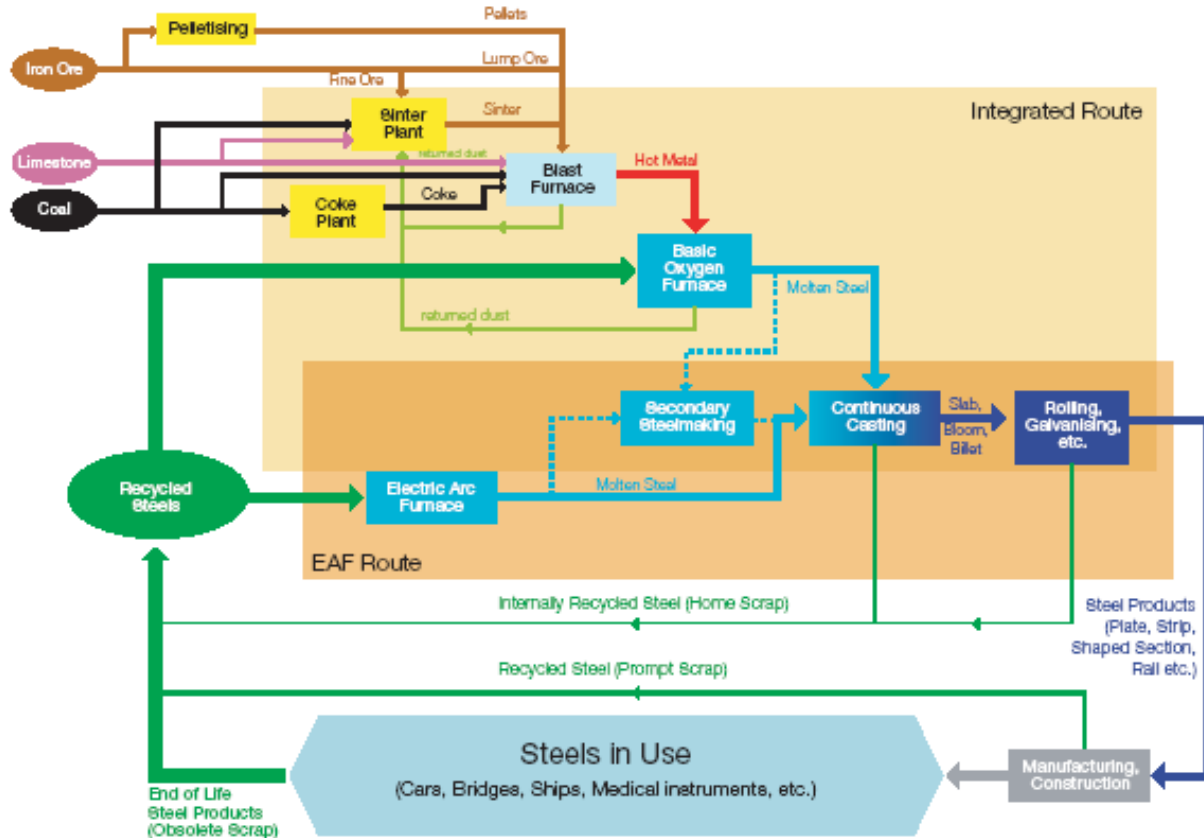
The production of steel at an integrated iron and steel plant is accomplished using several interrelated processes. The major processes are (1) coke production, (2) sinter production, (3) iron production, (4) raw steel production, (5) ladle metallurgy, (6) continuous casting, (7) hot and cold rolling, and (8) finished product preparation. The operations for secondary steelmaking, where ferrous scrap is recycled by melting and refining in electric arc furnaces (EAFs) include (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**.

The GHG emissions are generated as (1) process emissions, in which raw materials and combustion both may contribute to CO₂ emissions; (2) emissions from combustion sources alone; and (3) indirect emissions from consumption of electricity (primarily in EAFs and in finishing operations such as rolling mills at both integrated and EAF plants). The major process

units at iron and steel facilities where raw materials, usually in combination with fuel combustion, contribute to the GHG emissions include the following:

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

Steelmaking Routes: Integrated Route and Electric Arc Furnace Route



Source: International Iron and Steel Institute

Figure 1. Routes to steelmaking.

The primary combustion sources of GHGs include the following:

- By-product recovery 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). Additional information on the estimated GHG emissions is provided in **Appendix A (Table A-4)**.

The following paragraphs provide brief descriptions of iron and steel processes. More detailed process descriptions, a list of plants and locations, and other industry information are provided in **Appendix A**.

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 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 CO₂ 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 (CO₂) are emitted from the blast furnaces' stove stacks where the combustion gases from the stoves are discharged. The carbon in the CO₂ 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.

The **BOF** is a large, open-mouthed, pear-shaped vessel lined with a basic 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 CO₂. The large quantities of CO produced by the reactions in the BOF are converted to CO₂ by combustion at the mouth of the furnace in BOFs equipped with open hoods that draw in outside air or by flaring after gas cleaning in BOFs with tight-fitting closed hoods (called suppressed combustion). Final gas cleaning is performed by either venturi scrubbers or electrostatic precipitators for open hood BOFs; however, only venturi scrubbers are used on closed hood BOFs because of the explosion hazard from electrostatic precipitators if they were to be applied to the gas stream that is rich in CO. The major emission point for CO₂ from the BOF is the furnace exhaust gas that is discharged through a stack after gas cleaning. The carbon in the CO₂ exhaust comes mostly from the 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 EAFs 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 CO₂ and CO, which are removed from the vessel. CO₂ emissions from EAFs are generated primarily during the melting and refining processes, which remove carbon as CO and CO₂ from the charge materials and carbon electrodes, and smaller quantities of CO₂ are generated from the use of oxy-fuel burners by EAFs that are equipped with them. The emissions from the EAF are captured and sent to baghouses for removal of particulate matter (PM).

The steel produced by both BOFs and EAFs 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, 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. 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. 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. The EAF facilities burn natural gas almost exclusively in their combustion units, whereas integrated 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 machinability and formability. Ladle reheating uses natural gas to keep the ladle hot while waiting for molten steel.

II. Energy Programs and Management Systems

Industrial energy efficiency can be greatly enhanced by effective management of the energy use of operations and processes. U.S. EPA's ENERGY STAR Program works with hundreds of U.S. manufacturers and has seen 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.

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

The EMSs promote continuous improvement of energy efficiency through:

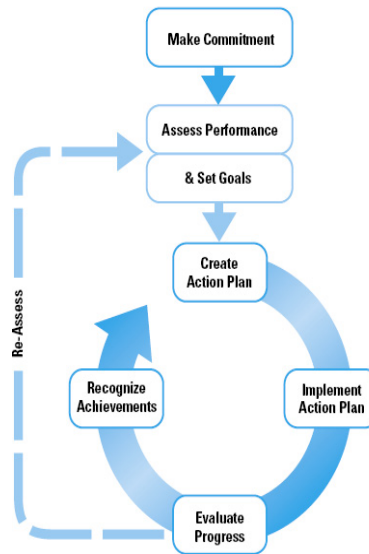
- Organizational practices and policies;
- Team development;
- Planning and evaluation;
- Tracking and measurement;
- Communication and employee engagement; and
- Evaluation and corrective measures.

For nearly 10 years, the U.S. EPA's ENERGY STAR Program has promoted an EMS approach. This approach, outlined in the graphic below, outlines the basic steps followed by most EMSs approaches (www.energystar.gov/guidelines).

In recent years, interest in EMS approaches 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 EMSs 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),^a and in the future from International Standards Organization (ISO), as ISO 50001.^b

While EMSs 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, EMSs can help achieve greater savings.

There are 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.

^a ANSI MSE 2001:200 can be found at <http://www.mse2000.net/>.

^b Will be available from the ANSI webstore at <http://webstore.ansi.org/default.aspx>.

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 EMSs with a wide range of associated costs (ENERGY STAR energy management resources are public while ANSI or ISO standardized approaches are costly). The effectiveness of an EMS is linked directly to the system’s scope, goals, and monitoring and recordkeeping. Benchmarks are the most effective measure for demonstrating the system’s achievements.

A. Sector-Specific Plant Energy Performance Benchmarks

Plant 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 0 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.

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 transnational approach in which all countries face similar benchmarks, a sectoral Clean Development Mechanism (CDM) 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.

B. Industry Energy Efficiency Initiatives

EPA's ENERGY STAR Program (www.energystar.gov/industry) and the U.S. Department of Energy's (DOE) Industrial Technology Program (www.energy.gov/energyefficiency) have led 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 CO₂ emissions.

III. Summary of Control Measures

Table 1 summarizes the GHG control measures presented in this document for integrated iron and steel plants, and Table 2 summarizes the measures for EAF steelmaking. Most of the information in the tables and the descriptions of the options in the next section were taken from a study by Worrell et al. (1999) that was conducted for EPA and DOE and subsequently updated (Worrell et al., 2009) in a study for EPA's Climate Protection Partnerships Division as part of the ENERGY STAR Program. The two tables include the emission reduction potential, energy savings, costs, and feasibility of each measure when such information was available. The following section provides more details and descriptions of the measures.

There are several important caveats associated with the estimated costs and savings presented in these tables that require caution in extrapolating the estimates in \$/ton to specific iron and steel plants. For many of the measures, the costs and savings are 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 costs could be quite different when applying the measures to other individual plants because of the numerous site-specific differences among plants that affect costs. In addition, some 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 are not included in the estimates. The calculation of cost effectiveness introduces additional uncertainty because of the additional variability and uncertainty associated with potential reductions in GHG emissions. The choice of which measures might be the most appropriate to implement at a given facility should be based on a detailed analysis by the facility's engineering or energy manager to assess site-specific costs, savings, and emission reductions.

Table 1. Energy Efficiency Technologies and Measures Applied to Integrated Steel Production in the U.S. (Worrell et al., 1999, 2009)

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)	Retrofit Capital Costs (\$/tonne of product)	Payback Time (years)
Iron Ore Preparation (Sintering)						
Sinter plant heat recovery	57.2	0.55	0.0	0.0	4.7	2.8
Emission optimized sintering						
Reduction of air leakage	2.0	0.0	0.0	0.0	0.14	1.3
Increasing bed depth	9.9	0.09	0.0	0.0	0.0	0.0
Improved process control	5.0	0.05	0.0	0.0	0.21	1.4
Use of waste fuels (e.g., lubricants) in sintering plant	19.5	0.18	0.0	0.0	0.29	0.5
Improve charging method						
Improve ignition oven efficiency						
Cokemaking						
Coal moisture control	6.7	0.30	0.0	0.0	76.6	> 50
Programmed heating	3.8	0.17	0.0	0.0	0.37	0.7
VSD COG compressor	0.12	0.0	0.0	0.0	0.47	21.2
Coke dry quenching	27.5	1.2	0.0	0.78	109.5	35.7
Additional use of COG						
Single chamber system						
Non-recovery coke ovens						
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	2.4
Injection of natural gas to 140 kg/ton iron	54.9	0.90	0.0	-3.1	7.8	1.3
Injection of oil						
Injection of COG and BOF gas						<1.0
Charging carbon composite agglomerates						
Top pressure recovery turbines (wet type)	17.6	0.0	0.11	0.0	31.3	29.8
Recovery of BFG	4.0	0.07	0.0	0.0	0.47	2.3
Hot-blast stove automation	22.6	0.37	0.0	0.0	0.47	0.4
Recuperator hot-blast stove	4.9	0.08	0.0	0.0	2.2	8.7
Improvement of combustion in hot stove						
Improved blast furnace control systems	24.4	0.40	0.0	0.0	0.56	0.4
Blast furnace gas recycling						
Slag heat recovery						
Steelmaking - Basic Oxygen Furnace (BOF)						
BOF gas plus sensible heat	46.0	0.92	0.0	0.0	34.4	11.9
VSD on ventilation fans	0.51	0.0	0.003	0.0	0.31	9.9
Improvement of process monitoring and control						
Programmed and efficient ladle heating						
Casting						
Efficient caster ladle/tundish heating	1.1	0.02	0.0	0.0	0.09	1.3

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)	Retrofit Capital Costs (\$/tonne of product)	Payback Time (years)
Near net shape casting - thin slab	728.8	3.5	0.64	-54.8	234.9	3.3
Near net shape casting - strip				25% less		
General Measures for Rolling Mills						
Energy efficient drives	1.6	0.0	0.01	0.0	0.30	3.2
Gate communicated turn-off inverters						
Install lubrication system			0.016			
Hot Rolling						
Proper reheating temperature						
Avoiding overload of reheat furnaces						
Hot charging	30.2	0.60	0.0	-2.1	23.5	5.9
Process control in hot strip mill	15.1	0.30	0.0	0.0	1.1	1.2
Recuperative burners	35.2	0.70	0.0	0.0	3.9	1.8
Flameless burners	60%	60%				
Insulation of furnaces	8.0	0.16	0.0	0.0	15.6	31.0
Walking beam furnace			25%			
Controlling oxygen levels and VSDs on combustion air fans	16.6	0.33	0.0	0.0	0.79	0.8
Heat recovery to the product		50%		32%		
Waste heat recovery (cooling water)	1.9	0.03	0.0	0.11	1.3	> 50
Cold Rolling and Finishing						
Heat recovery on the annealing line	17.5	0.30	0.02	0.0	4.2	4.0
Reduced steam use (pickling line)	9.9	0.19	0.0	0.0	4.4	7.3
Automated monitoring and targeting system	35.3	0.0	0.21	0.0	1.7	0.8
Inter-electrode insulation in electrolytic pickling line						
Continuous annealing						
General						
Preventive maintenance	35.7	0.43	0.02	0.03	0.02	
Energy monitoring and management system	9.5	0.11	0.01	0.0	0.23	0.5
Combined heat and power/cogeneration	82.1	0.03	0.35	0.0	22.7	6.1
High-efficiency motors						
VSD—flue gas control, pumps, and fans	1.5	0.0	0.02	0.0	2.0	10.7

Note: VSD = variable speed drive.

Table 2. Energy Efficiency Technologies and Measures Applied to Secondary Steel Production in the U.S. (Worrell et al., 1999, 2009)

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)	Retrofit Capital Costs (\$/tonne of product)	Payback Time (years)
Steelmaking - Electric Arc Furnace						
Improved process control (neural network)	17.6	0.0	0.11	-1.6	1.5	0.5
Adjustable speed drives (ASDs)			0.05		2.0	2-3
Transformer efficiency—ultra-high power transformers	10.0	0.0	0.06	0.0	4.3	5.2
Bottom stirring/stirring gas injection	11.7	0.0	0.07	-3.1	0.94	0.2
Foamy slag practice	10.6	0.0	0.07	-2.8	15.6	4.2
Oxy-fuel burners	23.5	0.0	0.14	-6.2	7.5	0.9
Post-combustion of the flue gases						
DC arc furnace	52.9	0.0	0.32	-3.9	6.1	0.7
Scrap preheating—tunnel furnace (Consteel)	35.2	0.0	0.22	-3.0	7.8	1.3
Scrap preheating, post-combustion—shaft furnace (Fuchs)	35.3	-0.70	0.43	-6.2	9.4	1.0
Engineered refractories			0.036			
Airtight operation			0.36			
Contiarc furnace			0.72			
Flue gas monitoring and control	8.8	0.0	0.05	0.0	3.1	4.3
Eccentric bottom tapping on existing furnace	8.8	0.0	0.05	0.0	5.0	6.8
Twin-shell DC with scrap preheating	11.1	0.0	0.07	-1.7	9.4	3.5
Casting						
Efficient caster ladle/tundish heating	1.1	0.02	0.0	0.0	0.09	1.3
Near net shape casting - thin slab	265.3	3.2	0.64	-54.8	234.8	3.3
Near net shape casting - strip				25% less		
Hot Rolling						
Proper reheating temperature						
Avoiding overload of reheat furnaces						
Energy efficient drives in the rolling mill	1.6	0.0	0.01	0.0	0.30	5.9
Process control in hot strip mill	15.1	0.30	0.0	0.0	1.1	1.2
Recuperative burners	35.2	0.70	0.0	0.0	3.9	1.8
Flameless burners	60%	60%				
Insulation of furnaces	8.1	0.16	0.0	0.0	15.7	31.0
Walking beam furnace			25%			
Controlling oxygen levels and VSDs on combustion air fans	16.6	0.33	0.0	0.0	0.79	0.8
Heat recovery to the product		50%		32%		

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)	Retrofit Capital Costs (\$/tonne of product)	Payback Time (years)
Waste heat recovery (cooling water)	1.9	0.03	0.0	0.11	1.3	> 50
General						
Preventive maintenance	15.0	0.09	0.05	0.03	0.02	
Energy monitoring and management systems	3.7	0.02	0.01	0.0	0.23	0.9

Note: DC = direct current; VSD = variable-speed drive.

Costs were taken primarily from Worrell et al. (1999) and adjusted from 1994 to 2008 dollars using the Chemical Engineering Plant Cost Index.^c In addition, costs and energy savings are presented as “per tonne”^d of product from the process (e.g., where “product” is steel from steelmaking furnaces, coke from coke plants, and sinter from sinter plants) 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 annual operating costs that are represented in the 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).

IV. Energy Efficiency Improvements

The iron and steel industry is energy intensive; consequently, many of the options available to reduce GHG emissions involve improved energy efficiency. Current energy consumption is approximately 19 million British thermal units per ton of steel (MMBtu/ton) (22.1 GJ/tonne) for integrated mills and 5.0 MMBtu/ton (5.8 GJ/tonne) for EAFs. DOE estimates that a reduction of 5.1 MMBtu/ton (5.9 GJ/tonne) (27 percent) is possible for integrated mills (half from existing technologies and half from research and development [R&D]). A reduction of 2.7 MMBtu/ton (3.1 GJ/tonne) (53 percent) is possible for EAFs (two-thirds from existing technologies) (DOE, 2005).

The American Iron and Steel Institute (AISI) stated that, with existing technologies and best practices, improvements in blast furnace efficiency are possible through optimized blast injection technologies and better sensors and process controls. Other near-term opportunities noted by AISI include blast furnace coal injection modeling (to reduce energy losses in the

^c 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).

^d 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.

cokemaking process) and optimizing processes through minimizing the generation of scrap and oxides (AISI, 2010).

The energy efficiency improvement options discussed by DOE (EPA, 2007a), listed below, are technically available but may not be economically viable in all situations:

- Preventive maintenance (0.21 MMBtu/ton (0.24 GJ/tonne) in potential energy reductions);
- Installation of energy monitoring and management systems for energy recovery and distribution between processes (0.06 MMBtu/ton) (0.07 GJ/tonne);
- Coal moisture control and dry quenching in the cokemaking process (0.22 MMBtu/ton) (0.26 GJ/tonne);
- For ironmaking (the most energy-intensive process), pulverized coal and natural gas injection, top pressure recovery turbines, hot-blast stove automation, and systems for improved blast furnace control (combined 1.34 MMBtu/ton) (1.56 GJ/tonne); and
- Casting/hot rolling energy efficiency opportunities include thin-slab casting with tunnel furnace (0.93 MMBtu/ton) (1.08 GJ/tonne).

Process-related opportunities noted by AISI (EPA, 2007a) for EAF steelmaking include the following:

- Improvements in process control, such as increased electrical energy transfer efficiency, reduced tap-to-tap times, and increased percentage of power-on time;
- Improved scrap preheating and charging practices; and
- Improved post-combustion practices.

A. Energy Efficiency Options for Integrated Iron and Steel Production

The following descriptions of mitigation options correspond to those in Tables 1 and 2 and are taken primarily from Worrell et al. (1999 and 2009). In many cases, the descriptions of measures were taken verbatim from these two research reports. 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.

1. Sintering

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 50–60 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 CO₂ emissions.

Reduction of Air Leakage

Reducing air leakage from the sintering plant reduces fan power consumption by approximately 2.7–3.6 kWh/ton (0.011–0.014 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 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 (lbs) 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 2–5 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. One plant 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 as 0.5 years.

Improve Charging Method

Limonite (brown iron 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. In order to reduce the fuel needed for ignition ovens, a heat-retention oven was removed from a conventional ignition oven with a large oven capacity, and an ignition oven with less capacity was introduced, in which the inner pressure of the ignition oven was regulated by controlling each windbox located immediately under the ignition oven. Moreover, 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 (SiO₂) with magnesium oxide (MgO), reduction of the basicity of the sinter, and the use of coarse coke breeze.

2. Cokemaking

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 0.11-0.18 MMBtu/ton coal (0.13-0.21 GJ/tonne) in carbonization heat requirements, while the strength of the coke^e is improved by approximately 1.7 percent and productivity by about 10 percent. The payback time was estimated as 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 a cost of \$0.43/ton (\$0.47/tonne) of coke and realized energy savings of 0.005-0.007 MMBtu/ton (0.006–0.008 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)^f 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 \$118-152/MMBtu (\$112-144/GJ) saved. Coke dry quenching has not been applied to any coke plants in the U.S.

^e 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.

^f Using net calorific value of 28,299 GJ/Gg coking coal.

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 17.7-33.5 in. (450-850 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.

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 tonnes/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.

3. Blast Furnace

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 lbs/ton (2 kg/tonne) of hot metal to approximately 260 lbs/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 \$45-50/ton (\$50-55/tonne) of coal injected. The payback time is estimated as 2.0 to 2.4 years.

For large-volume blast furnaces, the coal injection rate may be increased to 450 lbs/ton (225 kg/tonne) of hot metal. Resulting fuel savings were estimated to be 0.49 MMBtu/ton (0.57 GJ/tonne) of hot metal, with additional investment costs of \$7.38/ton (\$8.13/tonne) of hot metal. Operating costs may be reduced by \$1.41/ton (\$1.56/tonne) of hot metal.

Natural Gas Injection

Natural gas injection is typically applicable only to medium-sized furnaces having production rates of 1.4-2.5 million tons/yr (1.3-2.3 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 0.9-1.15 ton natural gas/ton coke (0.9-1.15 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 \$3.6-4.5/ton (\$4-5/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 6,400-16,000 ft³/ton (200-500 m³/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 (1 ton of oil replaces 1.2 tons of coke) (0.9 tonnes of oil replaces 1.1 tonnes of coke). With oxy-oil technology, the amount of oil injected can be increased by 100 percent to a level of 0.13 ton/ton hot metal (0.13 tonne/tonne hot metal). Like natural gas, oil contains hydrogen, leading to decreased CO₂ emissions.

Injection of COG and BOF Gas

Coke oven gas and BOF gas can also be injected into blast furnace. 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 replacement rate of COG 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. A compressor unit is required for COG injection resulting in an additional energy consumption of about 185 kWh/ton COG (0.73 GJ/tonne). Analysis indicates that injection of pulverized coal leads to higher energy effectiveness than that of COG. This technique was used in a U.S. Steel plant in Pittsburgh, Pennsylvania. Coke oven gas was used in the blast furnace to replace part of the natural gas that was injected in the furnace. It was found that it was more effective to use the COG in the blast furnace than to fuel boilers that feed steam turbines to generate electricity. The payback period was under 1 year.

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 14-36 kWh/ton (0.054-0.14 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 6-7 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 20-21 kWh/ton (0.080–0.085 GJ/tonne) of hot metal at a cost of approximately \$19-21/MMBtu (\$18–\$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 40-50 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 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 H₂) 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 CO₂ removal, (2) use with or without preheating, and (3) the 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 CO₂ Steelmaking (ULCOS) program.

Slag Heat Recovery

In modern blast furnaces, around 0.25-0.30 ton (0.23-0.27 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.^g One difficulty is that heat recovery from slag only becomes practical when the slag is granulated.^h If such a technique were to be developed, associated estimated savings would be approximately 0.30 MMBtu/ton (0.35 GJ/tonne) pig iron.

4. Basic Oxygen Furnace

BOF Heat and Fuel Gas Recovery

The BOFs 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 3,500°F (1,900°C). The exhaust gas from the open-hood BOF has no fuel value; however, both types of BOFs offer opportunities for heat recovery because of the high temperatures of the exhaust gas. Closed-hood BOFs suppress or prevent the intake of air, and the resulting exhaust gas at 3,000°F (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 BOFs are the closed-hood design, which has lower operating costs; however, no new BOFs have been installed in the U.S. in more than 30 years.

The closed-hood BOFs offer the best opportunity for both heat and fuel recovery. Although heat and fuel gas recovery from BOFs is very common in Japan and Western Europe, it is not implemented in the U.S., probably because the economics may be unattractive for retrofitting to 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.

^g 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.

^h 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.

The energy recovery would reduce CO₂ generation from the use of natural gas and electricity by approximately 0.05 ton of CO₂/ton of steel (0.05 tonne of CO₂/tonne of steel), which would offset a significant portion of the unavoidable generation of CO₂ from steelmaking (estimated at 0.11 to 0.16 ton of CO₂/ton of steel) (0.11 to 0.16 tonne of CO₂/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 reduced energy use at the BOF by about 50 percent and also 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 sensing 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 a management oxygen 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.

5. Casting

Continuous casting replaced the operations of reheating cast ingots in soaking pits, and then rolling the ingots in roughing mills to produce slabs. Approximately 97 percent of the steel in the U.S. is produced via the continuous-casting method. The energy savings over ingot casting is approximately 2.46 MMBtu/ton (2.86 GJ/tonne) of steel cast with cost savings of approximately \$28/ton (\$31/tonne) of steel. One estimate placed investment costs at \$63/ton (\$69/tonne) of steel.

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 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 1.2 years and 10 years, respectively. 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. Costs were estimated to be \$0.08/ton (\$0.09/tonne) of product, assuming a gas price of \$3.0/MMBtu (\$2.8/GJ), giving a payback period of 1.3 years.

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.

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 4.72-11.8 in (120-300 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.

This strip casting technology leads to considerable capital cost savings and energy savings. It may also lead to indirect energy savings due to reduced material losses. Operations and maintenance costs are also expected to drop by 20-25 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 80-140 kWh/ton

(0.32-0.55 GJ/tonne) for electricity and 1.0-1.3 MMBtu/ton (1.2-1.5 GJ/tonne) for fuel (Worrell, 2010).

A new development of thin slab casting and direct rolling is “Endless Strip Production.” 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).

6. General Measures for Rolling Mills

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. This section presents some energy efficiency measures that are applicable to both the hot rolling and cold rolling processes, and the following sections discuss energy efficiency measures that are specific to each. 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.

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 the high efficiency drives was estimated to be approximately \$0.27/ton (\$0.30/tonne) of hot rolled steel. The payback time is estimated as 3.2 years.

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.

Install Lubrication System

High roll loads of steel lead to increased roll wear and high energy consumption. In addition, specific combinations of rolling loads and speeds can cause stands to vibrate which

leads to a special type of roll banding and increased wear of the equipment. These problems can be solved by installing a lubrication system as was done at an EKO Stahl hot rolling mill. Energy savings due to this project were estimated to be about 4 kWh/ton (0.016 GJ/tonne), which is a savings of about \$0.28/ton (\$0.31/tonne).

7. Hot Rolling

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. 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). The heating temperature should therefore be carefully considered using a systems approach.

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.

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 between the two. 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 furnaces 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.

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 CO₂ 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).

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 840-1,020°F (450-550°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 70-80 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 as over 50 years.

8. Cold Rolling and Finishing

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.

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 ton/year (450,000 tonne/year) in the Midwest has an estimated cost of \$225 million. No information was available for payback time.

9. General Measures for Energy Efficiency Improvements

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. Opportunities for waste heat to power CHP exist with heat recovery in the sinter plant and in dry coke quenching.

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.

B. Energy Efficiency Options for Electric Arc Furnace Steelmaking

Opportunities to improve energy efficiency at EAF steelmaking facilities are described below. In addition, the casting, hot rolling, and other finishing processes at EAF facilities are similar to those described for integrated iron and steel plants. Consequently, the opportunities described earlier for these processes also apply to EAF facilities 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 EAFs, 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 CO₂ 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, CO₂, H₂, and O₂ 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.

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 2-3 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 5-7 kWh/ton (0.02-0.028 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 approximately half the EAFs in the U.S. 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 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 88-155 kWh/ft³ (11-20 GJ/m³) oxygen injected. Natural gas injection is typically 10 standard cubic feet per kilowatt hour, with energy savings ranging from 18-36 kWh/ton (0.72-0.14 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 570-1,470°F (300-800°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.

Direct Current Arc Furnace

The direct current (DC) arc furnace was pioneered in Europe, and these single-electrode furnaces have recently been commercialized in North America. The DC arc furnaces use DC rather than alternating current (AC). 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 454-544 kWh/ton (1.8-2.2 GJ/tonne) molten steel. Electrode consumption is about half that with conventional furnaces. This corresponds to 2.4-4.9 lb/ton (1-2 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 9-18 kWh/ton (0.036-0.072 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 EAFs operating in the U.S. and one in Mexico; most of these EAFs have been installed in the past 2 years, the oldest was 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 4–50 kWh/ton (0.016-0.20 GJ/tonne) and reduce tap-to-tap times by 8 to 10

minutes. A prominent example of its application to new EAFs 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 ton/yr (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.

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 furnaceⁱ 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 10-15 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.

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 ft³ (30,000 m³) 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

ⁱ 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.

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 are 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 and reduces the amount of natural gas needed for the burner.

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).

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 than 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.

C. Long-Term Opportunities to Reduce CO₂ Emissions (Worrell et al., 2009)

Increasing the primary energy efficiency of the production process will lead to a reduction in specific CO₂ emission. The energy efficiency measures that were discussed in the previous chapters therefore offer opportunities to reduce emissions. These reductions can be determined by multiplying the reductions in fuel and electricity usage with emission factors. Note that emission factors are dependent on the type of fuel used and the way electricity is generated.

A way to decrease CO₂ emissions from the blast furnaces ironmaking process is using hydrogen bearing materials such as steam, natural gas and waste plastics to substitute coke and coal. Apart from CO₂ emission reductions due to energy efficiency of resource utilization, there are several emerging technologies to mitigate emissions. However, none are currently commercially available or used at commercial scale. Development of these technologies may take decades.

The global steel industry collaborates in the ULCOS project to find opportunities to dramatically reduce CO₂ 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 CO₂ emissions from steel production. The aim of the ULCOS program is to reduce the CO₂ emissions by at least 50 percent.

ULCOS has selected four process concepts that could lead to a reduction of CO₂ emissions by more than half compared to current best practice. The following are the four breakthrough technologies identified:

- Top gas recycling blast furnace with carbon capture and storage (CCS);
- HIsarna with CCS;
- Advanced direct reduction with CCS; and
- Electrolysis.

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, or wood:

- Hydrogen reduction of iron ore has steam as a gas product instead of CO₂. Hydrogen can be produced from natural gas, by electrolysis of seawater, etc. Limitations are not technical, as technologies in the area of pre-reduction are very mature, and are related to the volatile issue of resource depletion in the longer term. Research projects are underway in different countries. In the U.S. the AISI, U.S. DOE, and the University of Utah investigate a process called Hydrogen Flash Smelting.
- The concept of using wood to make iron in a charcoal blast furnace is presently being applied in Brazil.
- 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 CO₂ 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 (MIT), AISI, and U.S. 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 CO₂ 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 converter-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

Carbon capture and storage involves separation and capture of CO₂ from the flue gas, pressurization of the captured CO₂, transportation of the CO₂ via pipeline, and finally injection and long-term geologic storage of the captured CO₂. Several different technologies, at varying stages of development, have the potential to separate and capture CO₂. 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.

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 CO₂ control technology, go to: http://www.epa.gov/climatechange/policy/ccs_task_force.html.

D. Emerging Technologies

According to AISI, 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 MIT); (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).

AISI lists the following additional areas as 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).

The R&D opportunities noted in the DOE 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 (0.5–0.7 MMBtu/ton [0.3-0.8 GJ/tonne]) (EPA, 2007a). **Appendix B** provides more details on active and completed research projects conducted by DOE and DOE’s partnerships.

1. 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 tons/yr (3.7 million tonnes/yr) of direct reduced iron (DRI) pellets, most of which will be processed in EAFs to produce 2.8 million tons/yr (2.5 million tonnes/yr) of steel slabs. This integrated steel-making route requires less energy and produces lower emissions than traditional integrated 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

2. EAF Steelmaking at an Integrated Plant

Wheeling-Pittsburgh Steel (now owned by Severstal) installed a state-of-the art EAF in December 2004 to replace its BOF for steelmaking. This is the first application of an EAF at an integrated mill to convert molten iron from the blast furnace into steel. The EAF is continuously charged with molten iron and scrap (BOFs and most EAFs 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).

Appendix A. Additional Background Details for the Iron and Steel Industry

A.1 Plants and Locations

Tables A-1, A-2, and A-3 list the operating plants (in 2009) for the 19 coke plants, 18 integrated plants, and 95 EAF plants, respectively. Several integrated 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 plants are in non-attainment areas for particulate matter with a diameter less than 2.5 micrometers (PM_{2.5}).

Table A-1. List of Coke Plants (AIST, 2009; EPA, 2001a)

No.	Company Name	City	State	No. of Batteries	Coke Capacity (tpy)	Type of Plant	Type of Coke	Type of Battery	Cogeneration
1	ABC Coke	Tarrant	AL	3	699,967	Merchant	Foundry	By-product	No
2	AK Steel ^a	Middletown	OH	1	1,200,000	Captive	Furnace	By-product	No
3	AK Steel ^a	Ashland	KY	2	2,000,000	Captive	Furnace	By-product	No
4	ArcelorMittal ^a	Burns Harbor	IN	2	1,877,000	Captive	Furnace	By-product	No
5	EES Coke/DTE Energy	Ecorse	MI	1	1,000,000	Merchant	Furnace	By-product	No
6	Erie Coke	Erie	PA	2	214,951	Merchant	Foundry	By-product	No
7	Gateway Energy & Coke	Granite City	IL	3	650,000	Merchant	Furnace	Nonrecovery	Yes ^b
8	Koppers	Monessen	PA	2	372,581	Merchant	Furnace	By-product	No
9	Mittal Steel	Warren*	OH	1	549,000	Captive	Furnace	By-product	No
10	Severstal ^a	Mingo Junction	OH	4	1,346,000	Captive	Furnace	By-product	No
11	Shenango	Neville Island	PA	1	514,779	Merchant	Furnace	By-product	No
12	Sloss Industries	Birmingham	AL	3	451,948	Merchant	Foundry	By-product	No
13	Haverhill Coke	Haverhill	OH	4	1,100,000	Merchant	Furnace	Nonrecovery	Yes ^b
14	Indiana Harbor Coke	East Chicago	IN	4	1,300,000	Merchant	Furnace	Nonrecovery	Yes ^b
15	Jewell Coke and Coal	Vansant	VA	6	745,000	Merchant	Furnace	Nonrecovery	No
16	Tonawanda	Tonawanda	NY	1	268,964	Merchant	Foundry	By-product	No
17	U.S. Steel	Clairton	PA	12	5,573,185	Captive	Furnace	By-product	Yes ^c
18	U.S. Steel ^a	Granite City	IL	2	584,000	Captive	Furnace	By-product	No
19	U.S. Steel ^a	Gary	IN	4	2,249,860	Captive	Furnace	By-product	No
	Total			58	22,700,000				

Note: tpy = tons per year.

^a Located at an integrated iron and steel plant (see Table A-2).

^b Recovery of waste heat from the battery stack.

^c Combustion of excess COG.

Table A-2. List of Integrated Iron and Steel Plants (AIST, 2009; EPA, 2001b)

No.	Company	City	State	No. of BOFs	Steelmaking Capacity (tpy)	No. of Blast Furnaces	Iron Capacity (tpy)	No. of Coke Batteries	Coke Capacity (tpy)	Sinter Capacity (tpy)
1	AK Steel	Ashland	KY	2	2,100,000	1	2,000,000	2	2,000,000	
2	AK Steel	Middletown	OH	2	2,640,000	1	2,300,000	1	1,200,000	
3	ArcelorMittal	Burns Harbor	IN	3	5,600,000	2	5,460,000	2	1,877,000	2,800,000
4	ArcelorMittal	Cleveland	OH	4	5,100,000	2	3,100,000			
5	ArcelorMittal	East Chicago	IN	2	3,800,000	2	3,100,000			1,200,000
6	ArcelorMittal	East Chicago	IN	4	6,250,000	3	6,500,000			1,100,000
7	ArcelorMittal	Weirton	WV	2	3,000,000	2	2,700,000			
8	ArcelorMittal	Riverdale	IL	2	1,100,000					
9	Republic Engineered Products	Lorain	OH	2	2,700,000	1	1,460,000			
10	Severstal	Dearborn	MI	2	4,100,000	1	2,190,000			
11	Severstal	Mingo Junction	OH	2	2,400,000	1	1,350,000	4	1,346,000	
12	Severstal	Sparrows Point	MD	2	3,375,000	1	3,100,000			3,430,000
13	Severstal	Warren	OH	2	2,040,000	1	1,460,000			
14	U.S. Steel	Braddock	PA	2	2,957,000	2	2,300,000			
15	U.S. Steel	Ecorse	MI	2	3,900,000	3	4,150,000			
16	U.S. Steel	Fairfield	AL	3	2,920,000	1	2,190,000			
17	U.S. Steel	Gary	IN	6	8,730,000	4	7,340,000	4	2,249,860	4,400,000
18	U.S. Steel	Granite City	IL	2	3,000,000	2	2,400,000	2	584,000	
	Totals			46	65,712,000	30	53,100,000	15	9,256,860	12,930,000

Note: tpy = tons per year.

Table A-3. List of EAF Steel Plants (AIST, 2009)

No.	Company Name	City	State	Steel Type	No. of EAFs	Capacity (tpy)
1	AK Steel	Butler	PA	C, S	3	1,000,000
2	AK Steel	Mansfield	OH	C, S	2	700,000
3	Allegheny Technologies	Brackenridge	PA	S	2	550,000
4	Allegheny Technologies	Midland	PA	S	2	600,000
5	Alton Steel	Alton	IL	C	1	700,000
6	Arcelor Mittal	Coatesville	PA	C, H, S	1	880,000
7	Arcelor Mittal	Georgetown	SC	C	1	550,000
8	Arkansas Steel	Newport	AR	C	1	130,000
9	Bayou Steel Corp.	LaPlace	LA	C	2	800,000
10	BetaSteel Corp.	Portage	IN	C	1	500,000
11	Border Steel Mills	Vinton	TX	C	2	250,000
12	Carpenter Technology	Reading	PA	H, S	6	180,000
13	Cascade Steel Rolling Mills	McMinnville	OR	C	1	750,000
14	Champion Steel Co.	Orwell	OH	C, H, S	1	6,000
15	Charter Steel	Cleveland	OH	C	1	700,000
16	Charter Steel	Saukville	WI	C	1	625,000
17	CMC Mills	Birmingham	AL	C, S	1	800,000
18	CMC Mills	Cayce-W. Columbia	SC	C	1	800,050
19	CMC Mills	Seguin	TX	C	1	1,000,000
20	Crucible Specialty Metals	Solvay	NY	H, S	1	50,000
21	Electralloy	Oil City	PA	H, S	1	60,000
22	Ellwood Quality Steels	New Castle	PA	C, H, S	1	400,000
23	Erie Forge and Steel Inc.	Erie	PA	C, H, S	3	385,000
24	Evrax Claymont Steel	Claymont	DE	C	1	490,000
25	Evrax Rocky Mountain Steel	Pueblo	CO	C	1	1,200,000
26	Finkl, A., & Sons	Chicago	IL	C	2	90,000
27	Geradu MacSteel	Baldwin	FL	C	1	1,100,000
28	Gerdau	Sand Springs	OK	C	2	600,000
29	Gerdau Ameristeel	Perth Amboy	NJ	C	1	800,000
30	Gerdau Ameristeel	Sayreville	NJ	C	1	750,000
31	Gerdau Ameristeel	Jackson	TN	C	1	892,000
32	Gerdau Ameristeel	Knoxville	TN	C	1	600,000
33	Gerdau Ameristeel	Vidor	TX	C	1	1,002,000
34	Gerdau Ameristeel	Monroe	MI	C	1	500,000
35	Gerdau Ameristeel (Gallatin Steel)	Warsaw	KY	C	2	1,600,000
36	Gerdau Macsteel	Fort Smith	AR	C	2	500,000
37	Gerdau Macsteel	Cartersville	GA	C, S	1	658,000
38	Gerdau Macsteel	Wilton	IA	C	1	917,000

(continued)

Table A-3. (continued)

No.	Company Name	City	State	Steel Type	No. of EAFs	Capacity (tpy)
39	Gerdau Macsteel	Jackson	MI	C, H	2	290,000
40	Gerdau Macsteel	St. Paul	MN	C	1	843,000
41	Gerdau Macsteel	Charlotte	NC	C	1	450,000
42	Haynes International	Kokomo	IN	H, S	2	20,000
43	Hoeganaes Corp.	Cinnaminson	NJ	C	1	112,000
44	Hoeganaes Corp.	Gallatin	TN	C	1	500,000
45	Keystone Steel & Wire Co	Peoria	IL	C	1	1,000,000
46	Kobelco Metal Powder of America	Seymore	IN	C	1	63,000
47	LeTourneau Inc.	Longview	TX	C, H	2	125,000
48	Lone Star Steel	Lone Star	TX	C	2	265,000
49	Mittal (formerly Bethlehem Steel)	Steelton	PA	C	1	1,200,000
50	Mittal (formerly Ispat Inland)	East Chicago	IN	C	1	500,000
51	National Forge	Irvine	PA	C, H, S	1	58,000
52	North American Hoganas Inc.	Hollsopple	PA	H, S	1	300,000
53	North American Stainless	Ghent	KY	S	2	1,600,000
54	North Star BHP Steel, LLP	Delta	OH	C	1	1,800,000
55	NS Group Inc./Koppel Steel Corp.	Ambridge	PA	C	1	550,000
56	Nucor Corp.	Birmingham	AL	C	1	600,000
57	Nucor Corp.	Trinity	AL	C	2	2,400,000
58	Nucor Corp.	Tuscaloosa	AL	C	1	1,300,000
59	Nucor Corp.	Blytheville	AR	C	2	3,000,000
60	Nucor Corp.	Bourbonnais	IL	C	1	850,000
61	Nucor Corp.	Crawfordsville	IN	C, H	2	2,400,000
62	Nucor Corp.	Flowood	MS	C	1	550,000
63	Nucor Corp.	Cofield	NC	C	1	1,400,000
64	Nucor Corp.	Norfolk	NE	C	1	1,100,000
65	Nucor Corp.	Auburn	NY	C	1	600,000
66	Nucor Corp.	Marion	OH	C	1	450,000
67	Nucor Corp.	Darlington	SC	C	1	1,050,000
68	Nucor Corp.	Huger	SC	C	2	3,450,000
69	Nucor Corp.	Jewett	TX	C	1	1,250,000
70	Nucor Corp.	Plymouth	UT	C	2	1,120,000
71	Nucor Corp.	Seattle	WA	C	1	1,100,000
72	Nucor-Yamato Steel Co.	Blytheville	AR	C, H, S	2	2,750,000
73	Oregon Steel Mills	Portland	OR	C,H	1	499,000
74	Republic Engineered Steels	Canton	OH	C	2	850,000
75	Severstal	Columbus	MS	C	1	1,700,000
76	Severstal	Steubenville	OH	C	1	2,400,000

(continued)

Table A-3. (continued)

No.	Company Name	City	State	Steel Type	No. of EAFs	Capacity (tpy)
77	SSAB North American Division	Axis	AL	C	1	1,250,000
78	SSAB North American Division	Muscatine	IA	C, H	1	1,250,000
79	Standard Steel	Latrobe	PA	C, H	1	59,000
80	Standard Steel	Burnham	PA	C, H, S	3	231,000
81	Steel Dynamics Inc.	Butler	IN	C	2	3,000,000
82	Steel Dynamics Inc.	Pittsboro	IN	C	1	720,000
83	Steel Dynamics Inc.	Columbia City	IN	C, H	2	2,000,000
84	Steel Dynamics Inc.	Roanoke	VA	C	1	650,000
85	Steel of West Virginia, Inc.	Huntington	WV	C	2	265,000
86	Sterling Steel Co., LLC	Sterling	IL	C	1	1,100,000
87	TAMCO	Rancho Cucamonga	CA	C	1	750,000
88	Timken Co.	Latrobe	PA	C, H	2	60,000
89	Timken Co., Faircrest Plant	Canton	OH	C, H	1	870,000
90	Timken Co., Harrison Plant	Canton	OH	C, S	3	358,000
91	TXI Chaparral Steel	Midlothian	TX	C, H, S	2	2,000,000
92	TXI Chaparral Steel	Petersburg	VA	C, H, S	1	1,200,000
93	Union Electric Steel Corp.	Carnegie	PA	C, H	1	35,000
94	Universal Stainless & Alloy Products, Inc.	Bridgeville	PA	H, S	1	150,000
95	V&M Star	Youngstown	OH	C, H	1	650,000
	Total					81,208,000

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

A.2 Greenhouse Gas Emission Estimates

Table A-4 provides preliminary estimates of GHG emissions from various iron and steel operations (based primarily on emissions factors and 2007 production rates). More precise and process-specific estimates of GHG emissions will be available in early 2011 when facilities report under EPA's mandatory reporting rule for GHGs. Blast furnaces and non-recovery coke plants are the largest emitters on a per process basis. Note that due to the economic downturn and lower production rates, GHG emissions may be lower for 2008-2010.

Table A-4. Preliminary Estimates of GHG Emissions (2007)

Type of Facility	Number of Facilities	Emissions (million tonnes of CO ₂ /yr)				
		Process Units	Miscellaneous Combustion Units	Indirect Emissions (Electricity)	Facility Total	Average per Plant
<i>Coke and EAF</i>						
By-product coke (standalone)	9	2.8	2.7		5.5	0.6
Nonrecovery coke	3	3.0			3.0	1.0
EAF facilities	92	4.8	18.6	22.8	46.2	0.5
<i>Integrated Iron and Steel Plants:</i>						
By-product coke (co-located)	6	1.2			1.2	0.2
Blast furnace	17	23.9			23.9	1.4
BOF	18	4.4			4.4	0.2
Sinter plant	5	2.7			2.7	0.5
<i>Totals</i>						
All Integrated Iron and Steel	18	32.2	16.8	6.5	55.5	3.1
All Facilities	130	42.8	38.0	29.3	110.1	0.8

Note: yr = year.

A.3 Overview of 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: cokemaking, integrated iron- and steelmaking, and EAF steelmaking (secondary steelmaking that primarily recycles steel scrap).

A.3.1 Sinter Production (EPA, 2001b; 2008b)

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. 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 iron and steel plants with sintering operations, and all of the sinter plants are part of an integrated iron and steel plant.

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 $\{[\text{CaO} + \text{MgO} (\text{calcium oxide plus magnesium oxide})]/[(\text{SiO}_2 + \text{Al}_2\text{O}_3) (\text{silicon dioxide plus aluminum oxide})]\}$; 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.

The primary emissions point of interest for the sinter plant is the stack that discharges the windbox exhaust gases after gas cleaning. The CO₂ is formed from the fuel combustion (COG or natural gas) and from carbon in the feed materials, including coke fines and other carbonaceous materials. Based on the Intergovernmental Panel on Climate Change (IPCC) emissions factor of 0.2 ton of CO₂/ton of sinter (0.2 tonne of CO₂/tonne of sinter) and the production of 14.7 million tons (13.3 million tonnes) of sinter in 2007, CO₂ emissions are estimated at 3.0 million tons (2.7 million tonnes) of CO₂/year. However, 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 (CH₄), when these gases are burned, a small amount of the unburned CH₄ is emitted with the exhaust gases. Consequently, sinter plants (and any other process that burns fuels that contain CH₄) also emit a small amount of CH₄.

A.3.2 Blast Furnace Iron Production (EPA, 2001b; 2008b)

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 its 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 CO₂ (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/ft³) (0.05 grams per cubic meter [g/m³]). 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 the iron and steel-making 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.

GHG Emissions

The vast majority of GHGs (CO₂) 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 CO₂ 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 CO₂ 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, CO₂ emissions from blast furnace stoves would be approximately 26 million tons (24 million tonnes) of CO₂/yr.

A.3.3 Steelmaking Process—Basic Oxygen Furnaces (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 CH₄) 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.

The major emission point for CO₂ from the BOF is the furnace exhaust gas that is discharged through a stack after gas cleaning. The carbon is removed as CO and CO₂ 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 CO₂/ton of steel (0.11 tonne of CO₂/tonne of steel) for carbon removed from the iron as CO₂. Applying the emission factor to the production of 44 million tons (40 million tonnes) of steel in BOFs in 2007 yields an estimate of 4.9 million tons (4.4 million tonnes) of CO₂/yr.

A.3.4 Steelmaking Process—Electric Arc Furnace (EPA, 2008b)

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 EAFs are designed to achieve a tap-to-tap time of less than 60 minutes.

The input material to an EAF is typically 100 percent scrap. Cylindrical refractory-lined EAFs 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 is 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.

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 CO₂ and CO, which are removed from the vessel.

The CO₂ emissions are generated during the melting and refining process when carbon is removed from the charge material and carbon electrodes as CO and CO₂. 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 CO₂ emissions.

The CO₂ emissions estimate of 5.1 million tons (4.6 million tonnes) of CO₂ for EAFs is based on the IPCC Guidelines emission factor of 0.08 ton of CO₂/ton of steel (0.08 tonne of CO₂/tonne of steel) and the production of 64 million tons (58 million tonnes) of steel in 2007.

A.3.5 Casting and Finishing (EPA, 2008b)

Casting

The steel produced by both BOFs and EAFs 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.

A.3.6 Other Steel Finishing Processes and Combustion Sources (EPA, 2008b)

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 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 plants. The CO₂ 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.

A.3.7 Coke Production (EPA, 2008b, 2001a)

Most coke is produced in by-product recovery coke oven batteries. However, of the 19 U.S. coke plants shown in Table 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 CO₂ 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 (1,100°C to 1,500°C). 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 CH₄, 6 percent CO, and 2 percent CO₂.

Non-recovery Coke Oven Batteries

As the name implies, the non-recovery cokemaking process does not recover the numerous chemical by-products, as previously discussed. All of the COG is burned, and instead of recovering the chemicals, this process offers the potential for heat recovery and 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.

GHG Emissions from Coke Plants

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 CO₂ emissions from the combustion stacks at by-product recovery coke plants for development of an emissions factor for EPA’s 2008 revision to AP-42 (EPA, 2008a). These tests averaged 0.21 ton of CO₂/ton of coke (0.21 tonne of CO₂/tonne of coke). Test results for a non-recovery battery were also obtained and analyzed. The average of three runs at Haverhill Coke resulted in an emissions factor of 1.23 ton of CO₂/ton of coke (1.23 tonne of CO₂/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 combustion stacks based on the 2007 production rate are estimated at 3.3 million tons (3 million tonnes) of CO₂ from non-recovery battery stacks at three coke plants and 3.1 million tons (2.8 million tonnes) of CO₂ from by-product recovery battery stacks at the 15 U.S. coke plants.

A small amount of CO₂ 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 2008 revisions to EPA’s AP-42 compilation of emissions 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 CO₂/yr.

Fugitive emissions occur during the coking process from leaks of raw COG that contains CH₄. 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.

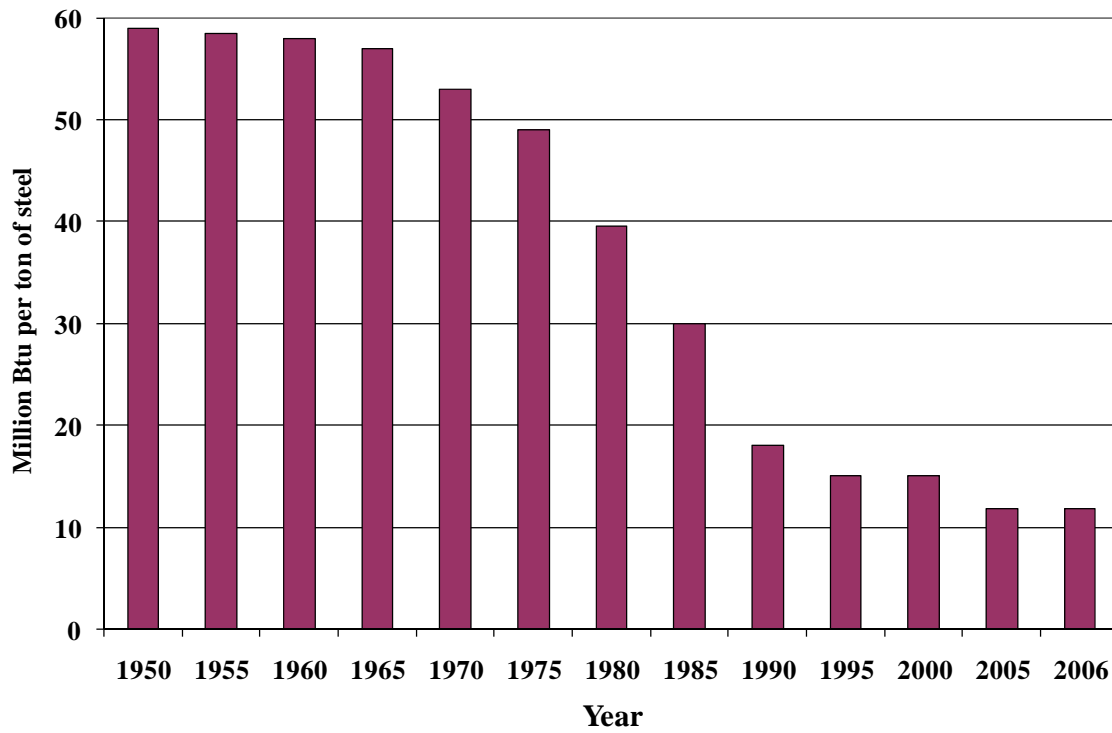
Many by-product recovery coke plants also have other combustion sources, primarily boilers and flares. These units use excess COG that is not used for underfiring the battery or shipped offsite for use as fuel in other processes. The IPCC Guidelines provide an emissions factor of 0.56 ton of CO₂/ton of coke (0.56 tonne of CO₂/tonne of coke) (assuming all of the COG is burned). Emissions from the combustion of COG in units other than the coke battery underfiring system are estimated at 0.35 ton of CO₂/ton of coke (0.35 tonne of CO₂/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., the nine 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 CO₂/yr.

A.4 Energy Intensity

As shown in **Figure A-1**, the U.S. iron and steel industry has reduced overall energy intensity for steel production dramatically since the 1950s (AISI, 2010). A large part of this decrease is due to the increasing proportion of steel recycled in EAFs since the 1970s—the energy intensity of secondary steelmaking is much less than the integrated iron and steel route (19 MMBtu/ton [22 GJ/tonne] for integrated and 5.0 MMBtu/ton [6 GJ/tonne] for EAFs). 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 A-5**, 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 A-6**), 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.



Source: American Iron and Steel Institute

Figure A-1. Historical energy consumption in the iron and steel industry.

Table A-5. Electricity Generation in the Iron and Steel Industry

Plant	Nameplate Capacity (megawatts)
Coke Plants	
Indiana Harbor Coke, East Chicago, IN ^a	94
Haverhill Coke, Haverhill, OH ^b	46
US Steel, Clairton, PA ^c	81
Gateway Energy and Coke, Granite City, IL ^d	139
Erie Coke, Erie, PA ^c	2.5
Total	362.5
Steel Plants	
Arcelor Mittal (was Ispat), East Chicago, IN ^c	263
Arcelor Mittal (was LTV), East Chicago, IN ^c	97
Arcelor Mittal (was Bethlehem), Burns Harbor, IN ^c	178
Arcelor Mittal (was LTV), Cleveland, OH ^c	45
Severstal (was WCI), Warren, OH ^c	20.5
Severstal (was Bethlehem), Sparrows Point, MD ^c	170
US Steel, Fairfield, AL ^c	82
US Steel, Gary, IN ^c	231
Total	1,086.5

^a Compiled from press releases. The cogeneration plant is owned by Primary Energy, a subsidiary of NIPSCO.

^b Compiled from press releases. 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.

^c From EIA/DOE, *Inventory of Nonutility Electric Power Plants in the United States 2000*. Energy Information Administration, U.S. Department of Energy. DOE/EIA-0095(2000)/2. January 2003.

^d Compiled from press releases. Planned to be fully operational in 2010.

**Table A-6. U.S. Slab Casting Units Installed 1994–2000^a
with Thin Slab Facilities Noted**

Facility	City	State	No. of Units	Year of Startup	Annual Capacity (1,000 tpy)	Product Thickness Range (in.)	Median Product Thickness (in.)
Mini-mills							
Nucor Steel ^b	Crawfordsville	IN	1	1994	1,000	2	2.0
Nucor Steel ^b	Hickman	AR	1	1994	1,000	2	2.0
Gallatin Steel ^b	Ghent	KY	1	1995	1,450	2.2–2.6	2.4
AK Steel ^b	Mansfield	OH	1	1995	750	3–5	4.0
Corus Tuscaloosa	Tuscaloosa	AL	1	1996	880	5.1	5.1
Steel Dynamics Inc. ^b	Butler	IN	1	1996	2,400	2.16	2.2
North Star BHP Steel	Delta	OH	1	1996	1,560	6.5	6.5
Beta Steel Corp. ^b	Portage	IN	1	1997	700	3.5	3.5
Ipsco Steel	Muscatine	IA	1	1997	1,250	5–6	5.5
Nucor Steel ^b	Berkeley Cnty	SC	1	1997	2,700	2.1–2.4	2.2
Steel Dynamics Inc. ^b	Butler	IN	1	1998	2,400	2.16	2.2
Nucor Steel ^b	Berkeley Cnty	SC	1	2000	2,700	2.1–2.4	2.2
Integrated Mills							
Geneva Steel	Provo	UT	1	1994	2,500	8.6	8.6
Rouge Steel Co.	Dearborn	MI	1	1996	1,300	8.0	8.0
Ispat Inland Ind Hbr	East Chicago	IN	1	2000	3,000	9.25	9.25
International Steel Gr	Sparrows Pt	MD	1	2000	2,200	10–12	11.0

^a Data taken from the 2003 Continuous Caster Roundup (AIST, 2003).

^b Uses thin-slab casting.

Appendix B. Emerging Technologies from U.S. Department of Energy (DOE) and DOE Partnerships

I. Active Research and Development Projects (DOE, 2009a)

The following projects are currently underway to improve the energy efficiency, environmental performance, and productivity of the steel industry. Emerging technologies are defined as technologies that are likely to be commercially available in the next 2 years.

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.

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 EAFs, and enables more effective use of sub-bituminous coal. Successful development of this new ironmaking

- process will produce potentially lower cost steel scrap substitutes. Also, 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

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.

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 manpower 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.

II. 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

III. Completed 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 (CO₂) 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

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